Modeling & Simulation for Affordable Manufacturing

Technology Roadmapping Initiative

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Notice

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1.0 EXECUTIVE SUMMARY

Modeling and simulation (M&S) technologies represent tremendous opportunities for radical improvement of our ability to design, develop, manufacture, operate, and support complex products – to reduce the time and cost of translating products from concept to delivered systems, to improve operational performance and availability, and to reduce total cost of ownership.

M&S faces many barriers. In its current state the technology is complex and expensive to implement, is limited in utility in all but a handful of narrow domains, and, despite increasing recognition of its value, is frustrated by the lack of a coordinated industry-wide strategy for evolution.

This document provides the foundation for that coordinated strategy. It is the product of two industry/government workshops, sponsored by the Air Force Research Laboratory (AFRL) Materials and Manufacturing Directorate and the National Science Foundation (NSF), and facilitated by the Integrated Manufacturing Technology Initiative, Inc. (IMTI). These workshops brought together more than 60 representatives of the nation's technology community to define a common vision for development and application of M&S technologies in manufacturing.

The Modeling & Simulation for Affordable Manufacturing Roadmap defines more than 75 top-level goals and 250 supporting requirements for research, development, and implementation of M&S technologies and capabilities. Subsequent processing by the workshop participants distilled these needs into four focused, high-level goals:

1) **Automated Model Generation** – Develop techniques to enable automated generation and management of models at various levels of abstraction for multiple domains.

2) **Automated Model-Based Process Planning** – Provide the capability to automatically generate manufacturing process plans based on product, process, and enterprise models, with integrated tools to evaluate producibility of features, resources, and repeatability.

3) **Interoperable Unit Process Models** – Develop a shared base of robust, validated models for all materials and manufacturing processes to enable fast, accurate modeling simulation of any combination of processing steps.

4) **Scaleable Life-Cycle Models** – Provide the capability to create and apply scaleable product life-cycle models in every phase of the life cycle and across all tiers of the supply chain.

These topics provide a <u>framework for investment to deliver leap-ahead advances</u> that directly benefit the bottom line for both industry and government. Separate white papers on each of these topics are available on the IMTI web site at <u>www.imti21.org</u>.

It is the consensus of the project participants that M&S users and developers should join forces with government sponsors specifically to launch implementation of the recommended research and development (R&D) actions. The technical challenges are significant, and <u>focused collaboration is essential to delivering the solutions</u> that industry and government need.

1.0 INTRODUCTION

In May 2002, more than 60 representatives of the nation's technology community convened in Orlando, Florida to define a common vision for development and application of modeling and simulation (M&S) technologies in manufacturing. Co-sponsored by the Air Force Research Laboratory (AFRL) Materials and Manufacturing Directorate and the National Science Foundation (NSF), the workshop brought together representatives from more than 40 organizations representing a broad cross-section of the nation's manufacturing community. Their goal: to identify M&S technology advances that will radically reform the manufacturing phase of the product acquisition cycle – reducing the time and cost required to move from idea to delivered product, and improving all aspects of life-cycle support while reducing total cost of ownership.

1.1 BUSINESS DRIVERS FOR IMPROVED MODELING & SIMULATION

Despite significant progress in recent years, acquisition span times remain far too long to support a responsive defense community that can react quickly to changing global missions and technology advances. This increases the danger of fielding outdated technologies, inflates development costs, and jeopardizes implementation milestones. Design changes to respond to revised performance requirements or budgets are common throughout the development cycle, further increasing the time and cost of moving products from the concept definition phase to production readiness.

DoD has made significant investments in M&S under the aegis of the DoD Modeling & Simulation Master Plan (DoD 5000.59-P) and initiatives such as Simulation Based Acquisition (SBA). However, the focus of these efforts has primarily been on synthetic environments, operational simulation frameworks such as HLA (High Level Architecture), and distributed interactive simulation to support wargaming, operations analysis, and training (Figure 1-1). Such tools are vital to developing and refining system-level requirements as an input to the acquisition process, aiding in understanding the relationship of needs and costs across the entire life cycle of the weapon system. They are also reducing the cost and improving the quality (and safety) of training by enabling warfighters to train realistically in the virtual realm and – ultimately – in distributed environments that integrate both live and virtual forces.

Tank Driver & Gunner Training

Distributed Interactive Wargaming & Weapons/ Tactics Training

Design Optimization for Support & Maintenance Ergonomics

Figure 1-1. DoD is making extensive investments in M&S technologies to reduce the costs of training and operational readiness.

However, excluding high-visibility programs such as Joint Strike Fighter, focus on M&S in the product design and manufacturing aspects of the acquisition process has been inadequate to drive radical improvements. The DoD M&S Master Plan does address a broad vision for exploitation of M&S in system development (Figure 1-2); however, this vision does not extend much beyond the identification of virtual prototyping and virtual testing as tools for streamlining the development process.

| Develop Warfightig Concepts | | Virtual Prototypes of new System Capabilities |

PERFORMANCE MODELING

Logistics Concepts
Signature
Weight/Mass
Lethality
Vulnerability
Mobility

ENGINEERING TRADE-OFFS

- REQUIREMENTS DEFINITION

- PERFORMANCE CONSTRAINTS/ OPPORTUNITIES

- BALANCED DESIGN SPECIFICATIONS

- RAM AND LOGISTICS IMPLICATIONS

- HUMAN SYSTEMS ENGINEERING

- CRITICAL SYSTEM CHARACTERISTICS

Iterative Electronic Prototyping

| Phase O : Concept Exploration & Definition | Phase I: Demonstration & Validation | Phase II: Engineering & Manufacturing Development | Phase III: Production & Development | Phase IV: Operations & Support |

Payoff
Compress Time and Reduce Cost of Acquisition

"The foundation of the acquisition process, the operational requirement and its transitioninto system terms, can be improved through the use of modeling and simulation"..."Accounting for human performance early in system acquisition improves system capability and enhances the test and evaluation process to predict operational performance."
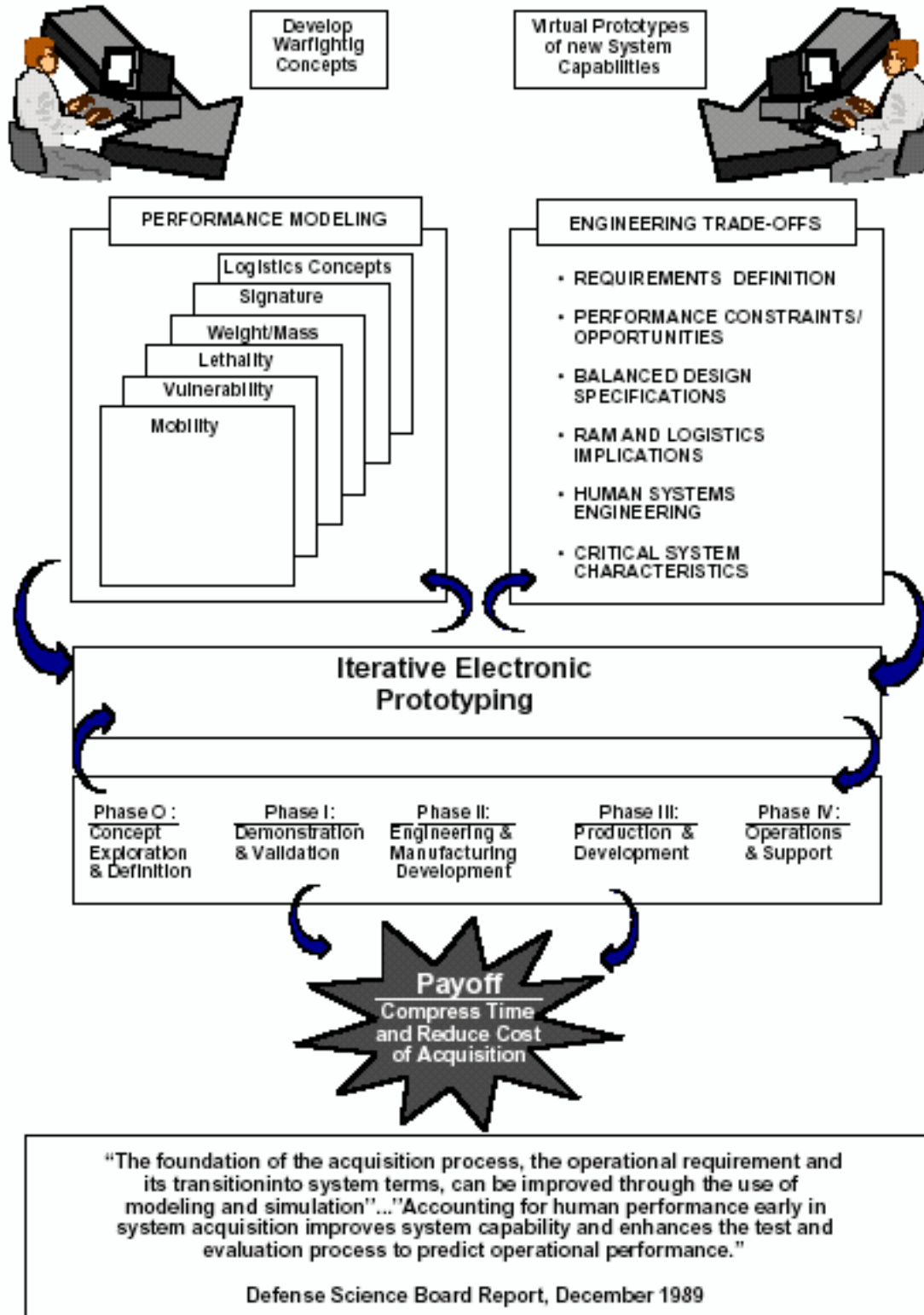
Defense Science Board Report, December 1989

Figure 1-2. Vision of M&S Support to the Acquisition Process
(from the DoD Modeling & Simulation Master Plan, DoD 5000.59-P)

Better integration of the design and manufacturing phases is widely accepted to be a key driver of reducing time from concept to delivery. The disciplines of concurrent engineering and integrated product/process development (IPPD) have made great strides towards integrating producibility and other manufacturing concerns in the design process. However, for major system acquisitions the gap between completion of concept definition and delivery of the first production unit remains one measured in years. Also, despite better integration of the design and manufacturing domains, a "final" production configuration still undergoes numerous changes after delivery of the first unit. This greatly complicates operation and maintenance (O&M), since training, maintenance, repair, and logistics supply must support each production variation.

Modeling and simulation is the key to optimizing the total product and system design before production; for optimizing the design for speed, quality, and affordability in production; and for optimizing the production processes so that they are in place and ready to execute upon production go-ahead. Maturation of the enabling technologies will enable system developers to slash months and years of development time and reduce costs by 50% or better from current design/build/test/fix practices.

What M&S brings is the ability to iteratively evaluate, test, and <u>validate</u> product and process designs in the virtual realm. This will radically reduce the number of formal design changes that must be implemented in the development process. AFRL reports that one recent weapon system program had 90,000 engineering drawing revisions at an average cost of $16,980 per revision – more than $1.5 billion because the design process couldn't "get it right the first time."[1]

A certain percentage of design change is unavoidable – requirements do evolve over time in response to external factors. Budget changes may dictate redesign to fit reduced funding profiles; revised threat/competitive assessments may dictate higher performance; or a newly emerging technology may offer improvements in cost or capability that warrant inclusion. However, M&S will not only enable designers to minimize unnecessary changes, it will enable them to respond quickly to desired changes, thus reducing impact on acquisition time and cost.

1.2 M&S TECHNOLOGY CHALLENGES

While the benefits of improved M&S may be difficult to quantify, there is no disagreement that the potential for benefit is profound. All of the technology-focused federal agencies are pursuing major initiatives in the form of studies and R&D programs. Table 1-1 identifies a few of the notable activities as of March 2001.

Table 1-1. Recent Federal Initiatives in M&S

Program	Agency
Advanced Engineering Environments	National Research Council
Defense Manufacturing in 2010 and Beyond	National Research Council
Engineering of Complex Systems (ECS)	Office of Naval Research
Engineering Research Center for Computational Field Simulation	NSF
High Level Architecture (HLA) for Distributed Simulation	DoD
Intelligent Synthesis Environment (ISE)	NASA
MISSION	NIST
Simulation Assessment Validation Environment (SAVE)	USAF
Simulation Based Acquisition (SBA)	DoD
Simulation Based Design (SBD)	DARPA
Systems Integration for Manufacturing Applications (SIMA)	NIST

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[1] *Integrated Manufacturing Simulation for Affordability, A White Paper*, AFRL, March 2001.

Although much has been accomplished in the development and application of M&S, there is still much to do. M&S applications have revolutionized product design over the last two decades; integration of applications into design "systems" has streamlined the design-to-manufacturing process. Manufacturing process simulation is providing the ability to make better decisions from a wider range of options. However, process simulation is focused on a case-specific basis with simulation tools tailored to high-need areas. As a result, there remain significant gaps in M&S technology – particularly in the provision of a general toolset that can be integrated across diverse manufacturing processes. The tools have matured and examples of impact have become more prevalent, but the ultimate success – the pervasive application of M&S tools to greatly reduce life-cycle product cost – is yet to be realized.

M&S must become THE method for product and process design. This requires both technological and cultural change. M&S tools are too often the domain of experts whose work is parallel to the product development effort. To integrate into the critical path, M&S must be used by the design team as an extension of its normal activities. The results must be presented in forms that can be understood and applied, without waiting for analysis and expert interpretation. The systems must be on-line as part of the design process and results must be timely. These technological capabilities will enable a shift in the design and manufacturing culture to the routine use of a rich suite of M&S tools to optimize designs quickly for performance, cost, and manufacturability.

In March 2000, AFRL convened a Technology Blue Ribbon Panel (TBRP) to address issues and challenges related to M&S for manufacturing in the defense community. The TBRP effort conducted an extensive research of published studies and conference and workshop proceedings to identify manufacturing M&S technology voids and barriers to implementation. In addition, the team conducted several one-day visits to various prime contractors, government organizations, and software vendors to identify and validate technology voids and gain insight into each company's needs and current information technology modernization plans. At a high level, the TBRP identified five technology voids it considered critical:

1. Physical representation
2. New and improved tools
3. Database integration
4. Ease of use
5. Training.[2]

The Barriers

Although there has been a significant increase in the capabilities of commercially available M&S tools over the past several years, there are still many holes. The amount of time it takes to develop models and run simulations is too large to allow widespread use of the technology. Improvements in terms of rapid modeling, model modification, and analysis preparation can go a long way toward simplifying their use. In addition, the use of feature-driven designs and knowledge bases can significantly decrease modeling time. Tools that support multifunction optimization, process planning as a by-product of development, and real-time cost as an independent variable are either immature or nonexistent.

The development and maintenance of databases and knowledge bases for design is a challenging and significant investment for any company or industry sector. A knowledge base that includes design allowances, reliability, producibility, cost, and other essential information is critical to achieving significant reductions in design time and for accelerating the development and insertion of new materials and manufacturing processes into the future product realization process.

Another key problem with the current M&S state of the art is the lack of tool and data integration. Some vendors do provide a monolithic integration approach for their own tool suite; however, this does not support individual tool selection and is certainly not "open" in any sense. By developing and applying

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[2] *Meeting Minutes*, IMSA Technology Blue Ribbon Panel (TBRP), 19 April 2001.

open standards to appropriate design and analysis data, the M&S vendor community can provide a more flexible environment that will support best-in-class tools, legacy data, and will ultimately lead to widespread use of the technology. Many companies are investing heavily in master model systems to integrate databases across all aspects of their business. Integration of product engineering information is a high priority, but the larger strategy is to facilitate the transfer of information and data digitally among all enterprise functions. Integration of engineering, manufacturing, product support, and maintenance and repair knowledge will enhance the early design process and dramatically reduce the amount of design changes, quality problems, and time associated with fielding a new system. Master model systems that integrate CAD, CAE, and visualization tools with predictive models are being developed, with links to management functions, document management functions, and enterprise resource management (ERM) systems. These investments, while providing limited solutions for an internal architecture, will be difficult to implement across the extended base of suppliers and subsystem integrators, especially given the trend of increased outsourcing of engineering, manufacturing, and product support functions.

Design and manufacturing M&S tools available today tend to be training intensive and require experts to use them. Employing immersive environments and desktop visualization techniques along with a rapid modeling capability will significantly improve their usability. With these improvements, the training process becomes less cumbersome and reduces or eliminates the requirement for M&S experts.

A report by Antoinette Maniatty of Rensselaer Polytechnic Institute (RPI) provides an excellent overview of current barriers to improved M&S capabilities for design and manufacturing. Briefly summarized, these are:

- Inadequate simulation capabilities (fidelity of simulation codes and ability to simulate complex phenomena)

- Difficulty of use (expert knowledge needed for performing simulations)

- Lack of simulation synthesis (inability to integrate multiple codes, or integrate designs into the simulation environment)

- High cost of developing tailored simulation capabilities

- Inability to accommodate uncertainty

- Psychological and sociological barriers (acceptance of M&S tools as mainstream to the development process).[3]

1.3 FUTURE STATE VISION FOR M&S

In the future, modeling and simulation will be a fundamental tool and enabler of all manufacturing enterprise processes, from customer engagement through product design and manufacture to life-cycle support and ultimate recycle and disposal. Designers and customers will interact in a rich simulation environment that mirrors the real world and enables rapid, accurate exploration and tailoring of potential solutions to customer needs. The output of this interaction will be a thoroughly defined set of digitally captured requirements that define the product configuration, its capabilities, its acquisition and life-cycle costs, and the time and quantity for delivery.

Product design systems will intake these requirements and leverage a deep base of mathematically accurate models and powerful M&S tools – shared openly across the supply chain – to rapidly create and configure the detailed product design from the ground up. M&S tools will be used exclusively to analyze and optimize material selections, component/element designs, assembly sequencing, and subsystem/system performance attributes to create a complete, "multi-D" product model with all the information required to

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[3] Antoinette M. Maniatty, *Future of Computational Modeling and Simulation in Process and Product Design* (Draft), Rensselaer Polytechnic Institute, April 2002.

drive downstream manufacturing and life-cycle support processes. Virtual test environments will enable designers to subject their designs to "test to destruction" rigor without making a single physical prototype.

The manufacturing execution team will apply virtual process simulations coupled to validated material, equipment, and process models to design and optimize the manufacturing execution strategy, testing and "producing" product in the virtual realm to certify readiness for prroduction. These same models will be used as controllers in the actual product manufacturing process, with smart sensors and monitoring systems continuously comparing actual to model-defined performance parameters to keep the processes running in continuous conformance to requirements and specifications.

Models and simulations developed during the product/process development phase will be used directly in all aspects of life-cycle support, augmenting other M&S tools to provide "hands-on" training of product users and support personnel in the virtual realm, eliminating the long time lags that now exist between first-product delivery and full operational readiness. Maintenance and repair organizations will be able to bring up the multi-D product model from anywhere in the world to help troubleshoot problems and speed return to service, downloading needed part designs to their own fabrication shops to greatly reduce dependence on original equipment manufacturers and logistics chains.

This vision will be empowered and enabled by a rich M&S infrastructure that provides universally accepted and applied standards for creation, validation, integration, and representation of models and simulations. Supercomputer-class processors deployed to desktops and PDAs will remove computing power as a limiting factor in M&S applications. The existing small base of validated, proprietary models will evolve to populate a globally shared repository of virtually every material, every commodity product, every physical part, and every product produced by a U.S. manufacturer – with rigorous provisions for protection of intellectual property and national security information.

Achieving this vision will require an intense commitment by the nation's manufacturing technology community and the federal agencies that rely on and support U.S. industry. While many M&S initiatives are underway under government sponsorship and in private industry, greater focus and greatly increased cooperation, collaboration, and synergy are required to accelerate progress and attack the crosscutting barriers that affect multiple industry sectors.

This document defines a sweeping set of goals that will lead us to the vision. The participants in the Modeling & Simulation for Affordable Manufacturing workshop identified more than 75 top-level goals and 250 supporting requirements for required technology advances, then conducted a prioritization process to identify the key goals – the pressing needs – where industry, academia, and government must focus their resources to deliver near-term results. Following are the top 10 goals from the prioritization process, edited for clarity:

1. Automated generation of models at various levels of abstraction.

2. Complete awareness of cost factors, supporting decision making early and throughout the design and manufacturing life cycle.

3. Scaleable, comprehensive product life-cycle model with enabling architecture and data structures tailorable to all sectors and integrable across all levels of the supply chain.

4. Seamless integration of modeling systems to enable multi-discipline optimization delivering impact early in the design process.

5. Rigorous mathematical models to analyze uncertainty and provide validation and certification, including quantification of uncertainty.

6. A common object-driven data schema from which models are generated, assuring interoperability and reuse.

7. Automated generation of simulation-based process plans for manufacturing operations.

8. A solution to the interoperability problem of new, legacy, and proprietary systems and models.

9. Performance modeling systems that maximize the effectiveness of testing to realize "surprise free" product performance.

10. An interoperability framework for integration of materials, material processing, and manufacturing models and simulations.

A complete listing of the 37 goals voted on by the workshop group is provided in Appendix A of this document.

Subsequent processing of the workshop results defined four compelling requirements for which subsets of the workshop participants are currently working to create focused collaborative R&D initiatives:

- **Automated Model Generation** – Develop techniques to support the automated generation and management of interoperable models at various levels of abstraction for multiple domains.

- **Automated Model-Based Process Planning** – Provide the capability to automatically generate manufacturing process plans based on product, process, and enterprise models, with integrated tools to evaluate producibility of features, resources, and repeatability.

- **Interoperable Unit Process Models** – Develop a shared base of robust, comprehensive models for all materials and manufacturing processes to enable fast, accurate simulation of any combination of processing steps.

- **Scaleable Life-Cycle Models** – Provide the capability to create and apply scaleable product life-cycle models across every phase of the life cycle and through all tiers of the supply chain.

Separate white papers on each of these topics are available at www.imti21.org.

2.0 MSAM FUNCTIONAL MODEL

The roadmapping process for the M&S for Affordable Manufacturing (MSAM) initiative, using a methodology developed by IMTI, Inc., began with creation of a functional model (Figure 2-1) of the domain. The term "functional" is key. Simply put, the roadmapping process first identifies all of the M&S-related functions that the enterprise must perform in order to design, manufacture, and support its products. This assures that the roadmap focuses on identifying the capabilities required to advance and enhance the performance of those functions. A fourth element, Infrastructure, is included to capture crosscutting technology needs that support the other three functional areas.

The major components of the functional model are referred to as Elements. The breakdown units below the top level are referred to as the Sub-Elements. Summary-level definitions for each of the model Elements and Sub-Elements are provided in Table 2-1.
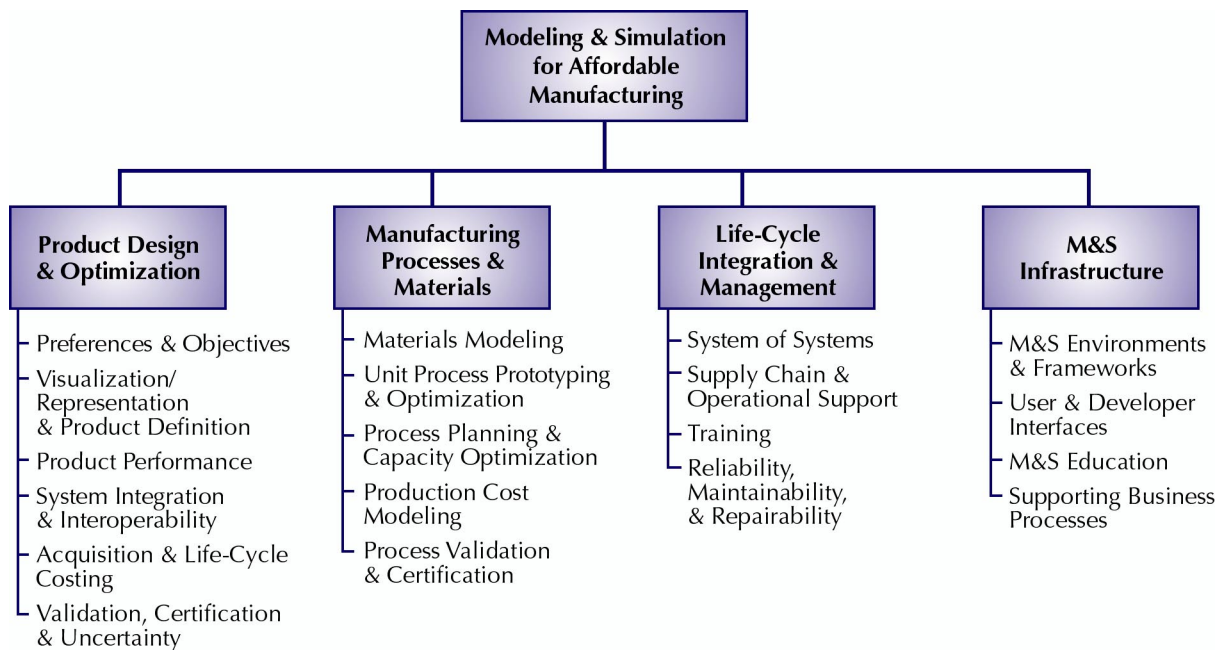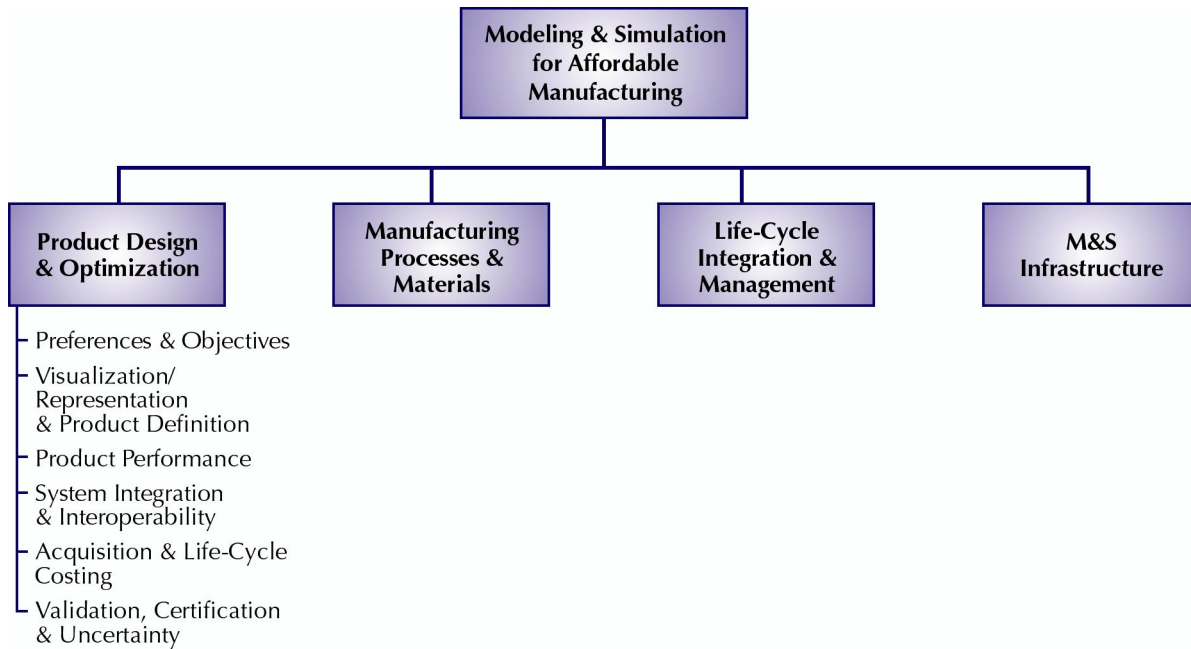
Modeling & Simulation for Affordable Manufacturing

Product Design & Optimization
- Preferences & Objectives
- Visualization/ Representation & Product Definition
- Product Performance
- System Integration & Interoperability
- Acquisition & Life-Cycle Costing
- Validation, Certification & Uncertainty

Manufacturing Processes & Materials
- Materials Modeling
- Unit Process Prototyping & Optimization
- Process Planning & Capacity Optimization
- Production Cost Modeling
- Process Validation & Certification

Life-Cycle Integration & Management
- System of Systems
- Supply Chain & Operational Support
- Training
- Reliability, Maintainability, & Repairability

M&S Infrastructure
- M&S Environments & Frameworks
- User & Developer Interfaces
- M&S Education
- Supporting Business Processes

Figure 2-1. The functional model provides a logical framework for development of R&D goals and requirements.

Table 2-1.
Element Definitions for the M&S Functional Model

PRODUCT DESIGN & OPTIMIZATION	
Preferences & Objectives	Includes all activities related to assisting the customer in understanding alternatives for products, in specifying preferences and objectives for that product, and in utilizing the customer input to create a basis for design. That design basis will usually take the form of requirements from which designs are created.
Visualization/ Representation & Product Definition	Includes all functionality associated with accurate visual portrayal/depiction of objects, processes, interactions, interfaces, and effects in a simulation environment, and underlying mathematical, science-based characterization and definition of modeled/simulated elements sufficient to accurately drive engineering, manufacturing, and other downstream processes. Includes the conceptualization, creation, capture, control, and depiction of the product and its associated features based on defined requirements and goals.
Product Performance	Includes all functionality associated with simulating and evaluating, in a virtual environment, performance attributes of the product such as size, weight, strength, material properties, operating environment, reliability, availability, maintainability, supportability, interoperability, and operational effectiveness attributes such as speed, lethality, survivability, aerodynamic performance, fluid dynamics, and similar attributes.
System Integration & Interoperability	Includes modeling and simulation related to integration of complex, multi-element/multi-component/multi-subsystem products. Includes physical interconnection, mechanical and electrical interfaces, chemical/material interactions, software interfaces, component accessibility, system reliability and related dependencies, and similar attributes. Includes all issues associated with the interoperation and interoperability of M&S systems.
Acquisition & Life-Cycle Costing	Includes determination of product cost and associated affordability tradeoffs with various price and performance factors. Includes specific cost factors related to overall product life cycle attributes, including hardware and software development; testing and operational evaluation; manufacture; operation and maintenance factors such as sparing, replacement/repair, transport, training; and environmental requirements such as recycle, reuse, and disposal.
Validation/ Certification, & Uncertainty	Includes all functionality associated with assuring that modeling and simulation codes operate from a valid scientific and experiential base, and that their applications and their products are accurate and verifiable in all respects. Further, it includes the understanding and quantification of uncertainty in modeling and simulation environments
MANUFACTURING PROCESSES & MATERIALS	
Materials Modeling	Includes all aspects of M&S related to capture, representation (both visual and mathematical), and manipulation of material properties, including hardness, ductility, malleability, conductivity, crystalline structure, viscosity, reactivity, porosity, resistivity, conductivity, and similar attributes.
Unit Process Prototyping & Optimization	Includes all aspects of M&S related to evaluation of effectiveness, quality, and efficiency of a new or modified manufacturing process, and tailoring to realize the best process results within defined parameters. Includes manufacturability aspects such as material selection, part and feature complexity, tolerances, assembly interfaces, process options, and similar factors.
Process Integration & Capacity Optimization	Includes all aspects of M&S related to evaluation of multiple interrelated manufacturing processes intended to produce single or multiple products, and tailoring to achieve the best results (cost, quality, throughput, and time) for the total manufacturing activity.

Production Cost Modeling	Includes all aspects of M&S related to the determination, prediction, and optimization of the cost of manufacturing a product given a definition of the product and its manufacturing processes.
Process Validation & Certification	Includes all aspects of M&S related to assuring that a manufacturing process or processes will perform consistently and reliably in accordance with the design intent and specifications.

LIFE-CYCLE INTEGRATION & MANAGEMENT

System of Systems	Includes all aspects of M&S related to evaluating and optimizing the attributes and performance of a product with respect to all other products with which it will interact in operational usage. Includes issues such as material and component compatibility and interchangeability, logistics support, physical and other interfaces, and the synergistic effectiveness of all interrelated systems to meet the customer's goals and requirements.
Supply Chain & Operational Support	Includes all aspects of M&S related to logistics with respect to design, optimization, and delivery of spares, consumables, and other support of the end product, including deployment and transport; provision of spares, consumables, and data; maintenance levels and concepts; and overall supportability.
Training	Includes all aspects of M&S related to design, optimization, and delivery of training for and with the product for operational use and support, including virtual and constructive training and integration of virtual and constructive training with live training.
Reliability, Maintainability, & Repairability	Includes all aspects of M&S related to design and implementation of servicing of the delivered product, including product, component, and material service life; and concepts and designs for operational troubleshooting, problem isolation, repair/replacement, and refurbishment for return to operational status.

M&S INFRASTRUCTURE

M&S Environments & Frameworks	Includes the common computing and information resources, methods, applications, tools, and codes needed to support any and all modeling and simulation requirements and enable integration and interaction of different applications and tools with necessary fidelity and speed. Includes all standards and protocols required to enable "plug and play" interaction of diverse models and M&S tools that create and use them across the geographically distributed extended enterprise (including its supply chains).
User & Developer Interfaces	Includes all visualization and command and control functionality required to enable users and developers to operate and interact with models and their associated M&S applications as an integrated element of any discipline/domain toolset. Includes the ability, for example, to invoke analytical simulation from directly within a CAD application and provision of timely supplementary information or assistance to support the user's activity.
M&S Education	Supports all functional domains (including managers and engineers) with education in the value, applicability and development and use of M&S and M&S tools.
Supporting Business Processes	Includes all aspects of enterprise management and program management and support that enable and facilitate the integrated application of M&S capabilities across different enterprise functions and across the various phases of the product life cycle.

3.0 PRODUCT DESIGN & OPTIMIZATION

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                    │ Modeling & Simulation│
                    │   for Affordable     │
                    │    Manufacturing     │
                    └─────────────────────┘
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| Product Design & Optimization | Manufacturing Processes & Materials | Life-Cycle Integration & Management | M&S Infrastructure |

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System Integration & Interoperability	Includes modeling and simulation related to integration of complex, multi-element/multi-component/multi-subsystem products. Includes physical interconnection, mechanical and electrical interfaces, chemical/material interactions, software interfaces, component accessibility, system reliability and related dependencies, and similar attributes. Includes all issues associated with the interoperation and interoperability of M&S systems.

Acquisition & Life-Cycle Costing	Includes determination of product cost and associated affordability tradeoffs with various price and performance factors. Includes specific cost factors related to overall product life cycle attributes, including hardware and software development; testing and operational evaluation; manufacture; operation and maintenance factors such as sparing, replacement/repair, transport, training; and environmental requirements such as recycle, reuse, and disposal.
Validation/Certification, & Uncertainty	Includes all functionality associated with assuring that modeling and simulation codes operate from a valid scientific and experiential base and that their applications and their products are accurate and verifiable in all respects. Further, it includes the understanding and quantification of uncertainty in modeling and simulation environments.

3.1 CURRENT STATE ASSESSMENT FOR PRODUCT DESIGN & OPTIMIZATION

Table 3-1 provides a summary-level view of the current state of M&S technology for product design, which is widely diverse in capability, degree of integration, and ability to apply collective knowledge in the design of modified or new products. There are impressive advances in visualization technologies, simulation capabilities, and integration of information and analysis tools, but these are limited best-practice applications driven by high needs that warrant the significant investments required to acquire and employ the enabling technologies.

Individual companies have made significant investments in modeling tools to achieve a differentiating product capability or respond to a critical business need. However, even in the high-tech aerospace sector, industry lacks the ability to perform multi-disciplinary, multi-scale optimization of products in a modeling environment. There is little electronic interaction between the product design community and the materials and manufacturing process designers. Collaborative design tools are emerging, but are not yet in widespread use. Product optimization remains a primarily iterative manual process managed using disciplines such as integrated product/process development (IPPD).

The ability to capture customer preferences as an input to product requirements is minimal, even with current scenario modeling and simulation capabilities. One best-practice example of a tool that can analyze multiple design options is Unified Parametric Vehicle™ (UPV) by Visteon Corporation (Figure 3-1). Automobile companies apply these tools in design and performance prediction for powertrain and climate cooling systems. Weather conditions, driving conditions, interior cooling, and powertrain cooling requirements can be modeled to analyze design options for engine thermal management systems against criteria such as weight, fuel economy, emissions, and occupant comfort. This allows cost-effective evaluation and refinement of a wider scope of design options in a shorter amount of time, with fewer downstream engineering and manufacturing changes.
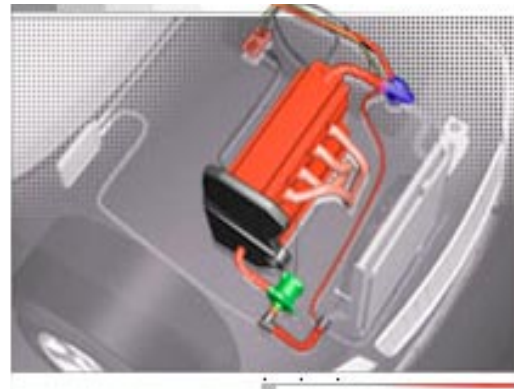

Figure 3-1. M&S applications such as Visteon's Unified Parametric Vehicle tool are helping manufacturers optimize designs before committing them to production.

Visualization technology is outpacing use in the product design environment. As mathematical rigor and geometric accuracy catch up with display and solid model fidelity, application of these technologies will expand rapidly. Today, primarily 3D surfaces are viewed in a 2D CAD medium. As 3D solids are applied in 360° visualization media with functionality such as tolerancing, interference, and collision detection – and mathematical accuracy – the value of these technologies will grow rapidly.

Table 3-1. State Map for Product Design & Optimization

Sub-Element	Lagging Examples	State of Practice	State of Art/ Best Practice
Preferences & Objectives	• This function is often bypassed – with requirements definition being the first step in product development • Specifications/objectives omit uncertainty considerations • Product development lacks the "voice of the customer" and is ill prepared for innovative thinking • Designs constrained by capital facilities; design considerations constrained – limits new process capability	• Systems engineering tools to specify preferences and objectives • Customer interviews • Matrix selection methods; Pugh, AHP • Operational analysis –flow down from battlefield, scenario, then the system of systems to components • QFD applied to record objectives and screen alternatives • Difficult to resolve conflicting objectives • Little optimization or determination of "best solutions" • IPD teams that start from objectives	• Preference surveys and studies; usually related to a marketing function • Set-based supplier design – Toyota • Financial community: developed tools to assist in the design of new financial securities, portfolios, different futures options • Preferences determined by in system of system environment experimentation, e.g. Joint Forces Command activities • Virtual cockpits in which customers can evaluate options in determining objectives and selecting alternatives
Visualization/ Representation & Product Definition	• Pervasive use of drawing-based design systems; digitizing artifacts • Geometry focus with 2D CAD • CAD systems that don't communicate with other systems (including other CAD systems) • Models that are not complete and are incapable of driving manufacturing applications; e.g., models that don't close • Models and the visualization are not complete and accurate enough to define the space and to identify all processes/components • Visualization that is not mathematically based and has limited value • No consideration of uncertainty in representations • Controllers and other things that don't have geometry but affect overall system	• Representations don't accommodate tolerances and deviations • Abstraction is in its infancy; data representations segmented by discipline (performance/cost) • Models often not validated; limited use in design/manufacturing applications • Visualization is geometry-based, does not support material & product attributes • Simulations don't explore the unknowns • No one authoritative representation that contains all information and data needed • Limited ability to query information to support the decision process; data filtering limits decision making value • Surface modeling is the state of practice • Collision detection represents a mature and useful capability	• PDES/STEP applications for rich exchange of product definition: Boeing, P&W, G.E. exchange full data for engines and configuration in the system • Virtual reality – Caterpillar and auto companies use multiple walls and caves for visual evaluation • Solid modeling driving downstream applications • 777 flythru (visual/camera perspective), digital mockup of airplane subsystems • IPIX – 360 view • Dynamic positioning of oil platforms • Honeywell – CAD representations of tolerancing information beyond nominal geometry to automatically generate tolerancing features • Digital mockup of DD21 destroyer including smart product models

Sub-Element	Lagging Examples	State of Practice	State of Art/ Best Practice
Product Performance	• M&S used for troubleshooting fixes, not for design • Performance models limited to operation and may not address life-cycle issues • Oversimplification of models that don't include all important parameters; low robustness of models • Most often capturing heuristics where the goal is the capture of fundamental physics • Lack of reality from idealized modeling assumptions yields flawed results	• Physics of failure entirely different than physics of performance – a distinction often missed • Modeling as designed vs. modeling as manufactured vs. modeling as aged is not typically captured • Models tend to be developed in same timeframe with designs, but are needed early in process in order to drive designs • Uncertainty not captured well • Models based on heuristics, not physics • Abstractions and multi-disciplinary models don't maintain their integrity	• Consistent and reliable applications of M&S tools for performance modeling • Intel ICs/M&S design is achieving projected performance • Visteon simulation-based design • Multi-D models that extend beyond geometry to include schedules • In automotive industry, simulation has almost replaced crash testing • Rich analysis model definition and management capabilities enabled by AP209
System Integration & Interoperability	• Subsystem interfaces frozen early, which limits scope of the design space that is evaluated by modeling systems • Integrated design environment limited by organization barriers and disciplinary stovepipes • Systems designs usually "top down"; little opportunity to evaluate options against preferences • Integration of models is ignored • Interoperability barriers limit ability to model integrated system (and process) designs • System models don't support "buildup" from components or "flowdown" to applications	• Models lack ability to abstract to needed level of detail • User choices limited by what vendors supply, and COTS means generic tools for large markets • Freezing of designs limits ability to make improvements • Design with constraints on the interfaces which get carried throughout • System engineering done independent of physical design activities • Concurrent engineering and integrated product teams	• Computer industry pioneered modular design, interoperable systems advances. • SEI Capability Maturity Models for information management • Integrated, model-based design to production demonstrations (JSF program, ship building, GM concept car) • FedEx/UPS/Logistics examples in total information integration and management of operations • System engineering/complex systems integration in best practice in many aeronautics companies
Acquisition & Life-Cycle Costing	• Costing requires process characterization information which is often not available – especially to designers • Cost models may not represent reality, are maintained individually, and poorly shared • Life-cycle issues often ignored in deference to short term focus • Models often inaccurate due to difficulties in forecasting life-cycle issues • Life-cycle modeling systems often stand alone without integration	• M&S is not required in government contracts, so opportunity is often lost • Investments in flexibility in process focus to protect life cycle investments • Web-based supplier databases allow suppliers to bid on specifics, not just commodities; e.g., Coviscint allows auto suppliers to bid on details • Funding for cost models provided for specific applications such as Composites Affordability Initiative • Customer-driven mandates – support early assessments	• Smart product models (JASSM, JSF) • Simulation of weapons loadout on JSF • Performance based supportability, contracting, logistics, etc., emphasizes the customer's needs satisfied through the life cycle; e.g., PBL P3 • Acquisition cost model for propulsion (sector-wide) • Simulation-based acquisition

In the current state, the attributes of materials and manufacturing processes and other enterprise criteria are not integrated with design or with product visualization and representation. The geometry representations are not complete, nor are they useable in the design and control of manufacturing processes. Process models and simulations are applied independently from design, and in general, results are communicated manually. Ford Motor Company engineers are addressing these challenges by developing the capability to integrate materials and manufacturing process attributes and models with the geometric representation of product, from both their own design environment as well as from supplied subsystems and components.
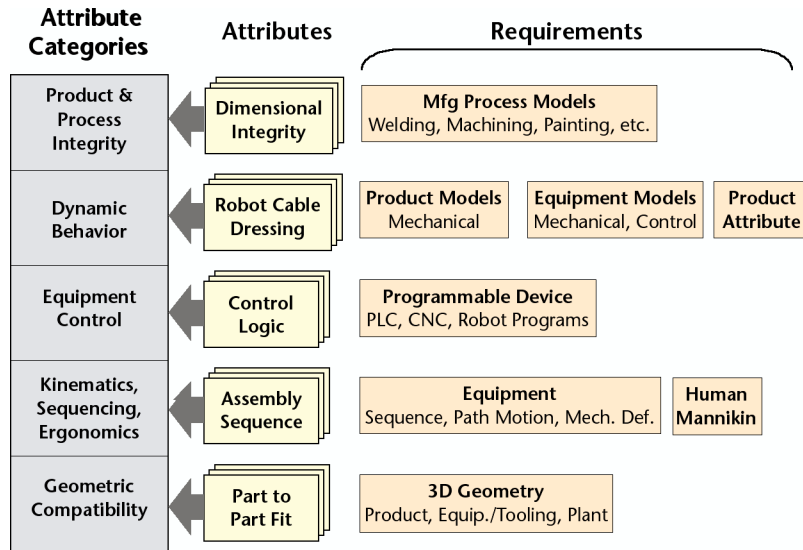

Figure 3-2. Ford's "knowledge integrated" design/manufacturing planning process supports best use of available M&S tools.

This challenge begins with product geometry and builds capability to analyze attributes such as part-to-part fit and part-to-tooling interactions and interference as shown in Figure 3-2. The challenge increases as considerations such as assembly, part movement, and human ergonomics are introduced into the analysis environment, followed by the increasing complexity of equipment control, behavior, and ultimately process models and the output from process simulations.

A current state assessment of M&S for product design is not complete without addressing systems engineering. The systematic progression from requirements to systems is well illustrated by the Vee Diagram (Figure 3-3).[4] Starting with the statement of need, design teams proceed through the processes defined on the left side of the V, to increasingly finer detail. At the component level, the systems are integrated to build the end product. At every stage of the process, the systems engineering approach applies modeling and simulation to identify areas of concern and fill the voids. NASA, as an example, uses a "modified V" approach – a little more detail with every step, aided by M&S tools.

Interoperability continues to be an industry challenge and bars efforts to achieve integrated systems that use and apply enterprise knowledge in early and detailed design phases. PDES/STEP is making progress in exchange of product definition data, and that progress will continue. Airframe designs requiring the integration of engine subsystem product definition and system geometry are examples of successful product data exchange between companies.
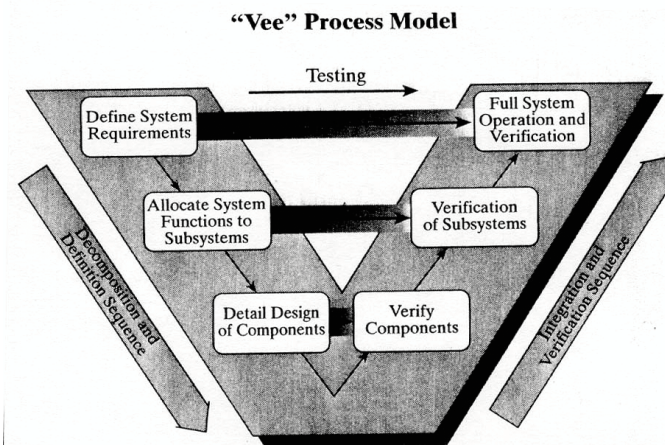

Figure 3-3. The Vee model provides a framework for application of M&S in systems engineering.

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[4] Benjamin Blanchard, Wolter Fabrycky, <u>Systems Engineering and Analysis</u>, Prentice Hall, New Jersey, 1998.

The current state of product performance modeling and simulation documents many model-based tools applied in product certification. The application of simulations to conduct crash testing has greatly minimized physical tests. Hard particle and bird ingestion models are accelerating certification testing for gas turbine engines. These capabilities, although demonstrating the real value of M&S tools, still lack truly accurate predictive capability – and the ability to incorporate the uncertainties necessary for effective validation.

Preferences & Objectives

Satisfying the preferences and objectives of the customer has always been the objective of product designers. Over the last decade, the ability to "delight" customers and tailor products to unique customer needs has risen to new visibility and importance. Customer perception is increasingly the basis of competitive differentiation for many companies.

The term "preferences and objectives" indicates a preliminary action in which design processes begin to capture the needs of the customer – leading to the definition of explicit requirements. In the current state, it is the view of experts contributing to this document that requirements and specifications focus too far downstream, shortchanging the exploration opportunity. To assure the best definition of what is wanted and needed, preferences should be processed and options explored long before requirements are cast.

The current state of establishing preferences and objectives has its foundation in the early 1990s, when requirements definition and capture systems became part of the design arsenal. Tools such as SLATE pioneered formal methods of requirements-driven design. Quality Function Deployment (QFD) and other systems engineering tools are now in common practice in product design and development. Concepts such as the Theory of Inventive-Problem Solving (TRIZ) are being applied in seeking creative and inno-vative solutions and in helping refine the available options to a set of best options.[5] The advent of Inte-grated Product Team (IPT) methodologies has given designers greater freedom to define how best to sat-isfy the customer's requirements within a given cost/schedule framework.

Major concerns in modeling and simulation of preferences and objectives fall into two categories. The first is simply the lack of capability. There is not enough attention given to capturing preferences and objectives as a precursor to modeling of product alternatives or creation of conceptual designs. Many attributes of a product cannot be captured in sufficiently discrete terms to create a model element, and it is more often true that customers have only a vague concept of what it is they actually want. Often, product innovation is driven more by the constraints of the manufacturing assets and capability as opposed to customer preferences. The second concern is associated with the decision processes. QFD, the Pugh concept selection matrix, and other methods are designed to screen alternatives in a multiple objective environment. There is strong argument that such screens provide limited useful results due to the ability to manipulate results and the lack of a mathematically rigorous process.

Current applications and systems do point the way to a future of solutions based on preferences and ob-jectives. In the manufacturing world, companies such as GE are developing "digital cockpits" that allow the customer, whether it be for a home appliance or a multi-billion-dollar battleship, to evaluate multiple options and specific preferences.

Visualization/Representation & Product Definition

Visualization/representation and product definition technology is advancing rapidly, with visualization capability outpacing practicality and applicability. Virtual reality (VR) headgear, "caves," and multiple walls are exciting tools for visualization, and are delivering value. A ProEngineer-based 3-D workgroup visualization system implemented at Honeywell's Kansas City Plant has demonstrated excellent usefulness in identi-fying interferences in complex electromechanical product designs (Figure 3-4). However, use of these technolo-gies in creating better designs has not yet had the widespread impact predicted. The visualization capa-

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[5] http://www.mazur.net/tqm/qfddetail.htm.

bility of a good 2-D screen coupled with mathe-matically accurate models remains much prefer-able to the best 3-D visualization without such accuracy.

In many cases, lack of model utility – beyond the visualization function – is a valid criticism be-cause models typically are incomplete, inaccurate, poorly defined as to uncertainty, and not useable across multiple systems. For visualization systems to realize their potential, they must be mathemati-cally accurate, compatible with other design sys-tems, and go beyond geometry to faithfully cap-ture underlying physics.

Product definition has been the focus of much of the funding and the activity in modeling and simulation. In the aerospace community, 3-D sur-

Figure 3-4. A 3-D workgroup visualization system at the Honeywell Kansas City Plant has demonstrated immediate impact in improving the manufacturability of complex electromechanical systems.

face modeling is the norm, with solid modeling gaining in application. Although accurate geometry is the most critical part of the design, especially for mechanical products, other vital attributes such as material properties, behavior characteristics, and process data are generally not supported. Material properties and manufacturing process models <u>must</u> be included in an integrated modeling and simulation solution.

Due to disparate CAD systems and a lack of interoperability, product data exchange is a major issue in product definition. This barrier exists between different functions within a company as well as between different companies and organizations. There is speculation that interoperability issues are decreasing due to the merger of many of the CAD companies and corporate commitments to single-source tool solu-tions. However, such commitment comes with risk, and does nothing to solve the problems of interoper-ability. PDES/STEP[6] has made great progress on the path to solution. Product models from disparate systems have been exchanged in large-scale demonstrations between systems and subsystems; most nota-bly with exchange of complete engine external configuration and aircraft body data between the propul-sion and airframe companies.

The final characteristic of the current state of M&S for product definition is the lack of completeness and intelligence in the model. Abstraction, which is the ability to migrate to higher or lower levels of fidelity or to generate sub-models to support specific functions, is in its infancy. In some programs, the product model is seen as the complete and adequate representation of geometry and all other needed information to drive all downstream applications. Such a rich product model enables integration of product and proc-ess modeling and supports automation of design functions and abstraction. There are good examples where pieces of activities support this direction. Activities such as the Federated Intelligent Product Envi-ronment (FIPER) program seek to provide tools to help companies integrate legacy and edge-of-the-art design and analysis tools into their product development process.[7] The "Supermodel" project led by STEP Tools, Inc. is integrating requirements-driven design tools to create product models that drive proc-essing applications. The automated feature extraction and feature-based tolerancing work being per-formed by Honeywell is also demonstrating excellent progress towards much-needed solutions.

Product Performance

Use of M&S for performance assessment is becoming pervasive in areas where physical testing presents major time and cost barriers or where liability/risk and safety certification warrant the investment. Crash simulation, for example, has greatly reduced physical crash testing for automotive applications. "Virtual

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[6] For more information on PDES/STEP, see http://pdesinc.aticorp.org.

[7] http://www.fiperproject.com/fiper/aboutfiper.htm.

ice" and "virtual birds" are reducing the scope of physical testing for gas turbine engines in certifying their ability to survive ingestion of foreign objects. Aerodynamic simulation has greatly reduced dependency on wind tunnels and product mockups early in the design phase, when rapid iteration of design concepts is vital to refining product performance requirements.

Modeling and simulation of thermal properties is highly developed in the electronics industry. Widespread use of commercial simulation tools to optimize designs at the chip, board, package, and integrated product level prior to physical prototyping has greatly improved reliability in both consumer and defense electronics applications (Figure 3-5).
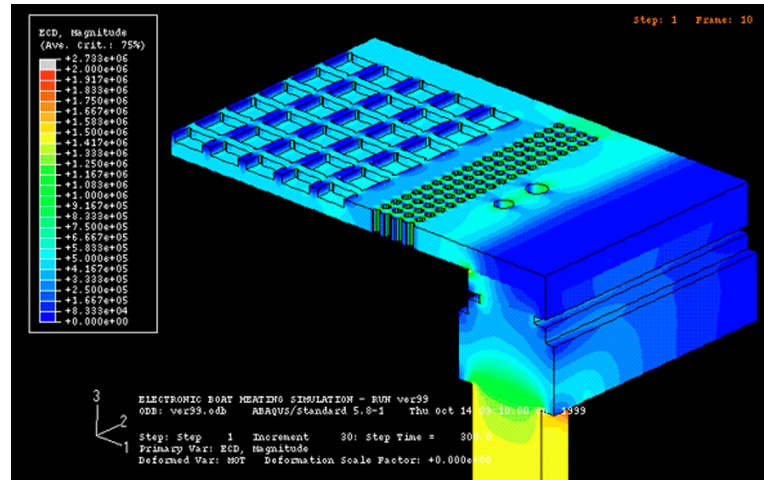

Figure 3-5. M&S of performance factors such as thermal loading is highly developed in the electronics industry and has greatly improved reliability in both commercial and defense applications.

While product performance modeling is maturing quickly in many domains, there are deficiencies in the current state that limit its utilization and highlight areas for improvement. There is a widespread need for standardized, automated, model-based performance analysis modules that can be applied to common types of products, such as printed wiring boards.[8] Cost is also a major barrier, particularly for smaller firms. For example, a leading finite element analysis (FEA) tool with only mechanical and thermal capability has an initial purchase price of $25,000 and an annual maintenance fee of $5,000[9]. Considering the functions provided barely scratch the surface of what is required to implement a comprehensive M&S environment for product performance analysis, most companies cannot afford to enter the M&S arena at a meaningful level.

There are gaping holes in the availability of models. For example, life-cycle reliability models are fairly new to the M&S world, and are not widely shared. The availability of performance models in the development timeline is also an issue. Typically, the models are developed and mature with the design; however, their greatest value is early in the process – to help guide and optimize the design. Instead of a smooth and seamless process of model-based design, the process is iterative, with the model finding flaws in the completed design instead of assisting in the creation of a flawless design. The problems here are both technical and cultural: few companies have adopted a philosophy of model-based design; predictive modeling capabilities are simply not mature.

Another characteristic of the current state of performance modeling is oversimplification. Many products and their operations are complex. Models and simulations that can't fully test the product contribute little to the optimization process. Inherently, models do not represent the as-manufactured condition with the associated range of manufacturing process variation and uncertainty. The ability to create models that fully and accurately represent products in terms of physics and mathematics is a critical void in present capabilities.

Life-cycle considerations must become an integral part of performance modeling and simulation. The ability to evaluate product performance under extreme conditions and electronically verify the performance of the product in all circumstances and for all aspects of the life cycle can be a huge asset in reduc-

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[8] Russell S. Peak, et al, *Towards the Ubiquitization of Engineering Analysis to Support Product Design*, Georgia Institute of Technology, 1999. http://eislab.gatech.edu/pubs/journals/ijcat-routinization/.

[9] Andrew J. Scholand and Russell S. Peak, *Internet-based Engineering Service Bureau (ESB) Technology*, Georgia Institute of Technology, August 1999. http://eislab.gatech.edu/pubs/reports/EL003/.

ing product ownership costs. The ability to trade off cost, performance, and risk in a balanced optimization equation is a powerful capability that has yet to be matured.

Emerging best practices point to future success. One of the areas of most maturity is in the automotive supplier industry. Companies such as Visteon and Johnson Controls are making strong use of simulation-based design and performance modeling in creating complex modular solutions and in fully analyzing all interrelations in the automobile – from vibration to noise to sound systems to comfort to climate control and more[10]. In the aerospace industry, utilization of simulation systems for digital design of both commercial and defense aircraft is advancing rapidly. Modeling of advanced flight systems that intelligently reconfigure for optimized performance is in the NASA pipeline. Lockheed Martin, Boeing, and others have sophisticated model-based design systems and are making them better. The Lockheed Martin IMD environment, although not focused on "seamless integration" but on point-to-point solutions, is a powerful package for model-based product design and development.

System Integration & Interoperability

The evolving vision of systems integration embraces a totally interoperable M&S environment. In this environment, a systems-level model sits at the top of a connected chain from each subsystem to each component in a totally connected structure. In the current state, progress is being made in that direction, but interoperability barriers and complexity challenges limit the ability to create truly integrated systems designs. Perhaps the largest barrier to meaningful progress is industry's present "standard" methodology for system design. In many cases, the system is conceptualized, and the subsystems are defined. To distribute and manage the workload, interfaces are defined between subsystems and each subsystem becomes its own design project. The fact that the subsystem interfaces are frozen early severely limits the design space that is evaluated and the options that can be pursued.

Progress is being made in this area. Perhaps the best example is the package service of FedEx and UPS. Each evening a totally connected network of computers, trucks, airplanes, people, and automated systems is put into motion to merge at key points and perform according to the models and the plans. While the distribution models are relatively predictable, they are not static. Fluctuations in loading and distribution, weather, national catastrophes, global politics, and many other variables come into play each day, but the system still operates. Great strides are also being made in the construction industry, with "4-D" models including schedule being generated for construction of complex facilities by Disney and others.

There are success examples in manufacturing. Intricate hierarchical models of complex systems such as automobiles, airframes, and ship structures, are being developed. DARPA has funded impressive modeling systems for ships that enable "click-down" walkthroughs of components and systems. Many high-tech small businesses, although having low-complexity products, are successfully implementing model-based systems that support their product and process designs from requirements definition to delivery of product.

Acquisition & Life-Cycle Costing

Simulation-based acquisition (SBA) and life-cycle costs are a high priority to DoD. This emphasis is driven by a need to better control cost, schedule, and risk in complex, highly engineered weapon systems. Many major systems are deployed over budget and with performance shortfalls, in time spans that result in fielding obsolete technologies. In response to these issues, DoD has set aggressive goals of reducing total cost of ownership by 30% and the time from program start to initial operational capability (IOC) by 50%. To achieve these goals, DoD established a three-faceted program of SBA Acquisition Culture, SBA Acquisition Process, and SBA Acquisition Environment. Simulation-based tools and information technology applications are targeted as part of the solution package in each of these areas. SBA calls for *virtual* development of systems through iterative improvement of their digital representation from concept

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[10] http://www.visteon.com/technology/capabilities/cae.shtml.

definition, through selection of best concepts based on life-cycle factors, through manufacture, and to retirement.[11]

The current state of SBA and life-cycle costing has critical voids that must be addressed. In many cases the incentive and business case is missing, as it is difficult to tie investments in early design to reduced ownership costs using current financial and accounting systems. If the government (and prime contractors) required extensive simulation and modeling as part of the contracting process, the costs could be justified as part of the business development expense or compensated by the procurement funding. The chief beneficiary of a model-based environment is the customer – through risk reduction, cost savings, and assured performance. Resolving the issue of where in the product life cycle the major benefits and savings are realized and who owns the investment responsibility for simulation-based acquisition is a critical imperative.

Availability of the right data, information, and knowledge is a prerequisite to SBA. Designers must have access to models of the enterprise's resources, including process models. Accurate and current cost models must be available for timely decision making during design, replacing the current reliance on "engineering judgment." In most cases, companies must create and maintain their own cost models, but they lack the ability to represent the costs throughout the extended enterprise. There is progress as projects like the Composites Affordability Initiative are building shared cost models, based on consensus of the major industry participants, based on understood processes and materials.

Life-cycle modeling presents a unique set of challenges. Comprehensive life-cycle performance data is essential for building accurate models, but is impossible to obtain because there are no systematic mechanisms in place to collect and share it. While it is possible in most cases to predictively model product performance, the increasing uncertainty inherent to long-term impacts of minor variables makes accurate prediction of life-cycle performance difficult, even for products with a long service history. As life-cycle models become a more important part of the acquisition process, these barriers will need to be addressed.

Validation, Certification, & Uncertainty

The current state for validation, certification, and uncertainty is one of poor definition. Industry practitioners are challenged to agree on what is even meant by the term "validation" as it applies to models. In general, a model is considered validated if what it produces matches reality. However, there are no standards or methods for certifying models and simulations, which is essential to creating repositories of models that can be shared across industry.

Inclusion of uncertainty is a vital factor in model validation. A model or simulation must deliver accurate results within defined conditions, boundaries, and parameters reflective of real-world conditions. The wider a range of variables and values a model can accommodate and produce consistent and accurate results, the more "robust" the model. It is even more important to understand the limits of a model – the point at which it breaks down because of the complexity of one or more variables or values. In the current state, uncertainty is rarely included to any degree of specificity.

In manufacturing processes, progress is being made in model validation. Tolerancing models and automated tolerancing systems are being built and applied to support design of manufactured parts. These examples point the way to improved capabilities. The concept of science-based models is moving from goal to application. The combination of experiential data with scientific principles and the development of a scientific basis for models from statistically valid experiments are yielding good results. Neural networks are being used to interpolate and extrapolate from a small amount of data to a broad range of valid model operation. The ability to build predictive models from an understanding of the science basis, including assessment of uncertainty, is an important objective in extending the state of the art in M&S.

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[11] http://www.msiac.dmso.mil/sba_documents/intro-fi2.doc.

3.2 FUTURE STATE VISION, GOALS, & REQUIREMENTS FOR PRODUCT DESIGN & OPTIMIZATION

Vision: Powerful, seamlessly integrated M&S tools will enable distributed design teams to quickly and accurately create product and process concepts and detailed designs that are optimized for the best balance of performance and affordability with respect to all customer requirements and objectives. The product model will serve as the input and control mechanism for all processes across the product life cycle, capturing and disseminating supporting data to drive continuous product and process improvement.

The model-based design environment of the future will consistently deliver best designs to satisfy a balanced set of objectives, for both the customer and the supplier. Rich and mathematically accurate visualization environments, augmented by real-time analytical tools, will allow users to interactively specify preferences and objectives and perform trade-offs for optimization. As each preference is specified, the user will see the impact in performance, cost, delivery, aesthetics, and other attributes of importance. From this interactive environment the attributes of the design will be developed and, in the background, the data structure that drives and supports the design process will be formulated.

A single product "object" model will emerge as the solution for automatically assuring that needed information is available and is delivered in directly useable form to the functions that need it. An integrated hierarchical structure provide the top-level (system) model housing the complete product definition, containing all information and data required to drive all analytical, manufacturing, and operational systems functions and their associated models and simulations. Top-level models will seamlessly integrate in a system-of-systems environment.

The future product model will no longer be a simple physical product representation coupled to a database of dimensions and other physical attributes. It will be a complete, dynamic virtual product containing and linking all information related to its manufacture, its performance, and its life-cycle processes. Reusable, scalable, self-populating models will be standard tools of product engineering and manufacturing, with the models often running in the background and determining what information they need to satisfy the requirements of the emerging specification. The models will be dynamic, continuing to adapt themselves to the environment of the enterprise and optimizing around a balanced slate of user preferences and business level necessities.

Interoperability will not be an issue in the environment of the future. Standards will emerge that enable all models to exchange needed information through automated ontologies, semantic understanding, and self-integration techniques.

The acquisition process will be model-driven, with life-cycle cost and performance well understood. Risks will be mitigated by a clear understanding of uncertainties, which will enable operation in "safe areas" well away from the bounds of failure. The resulting product will be fast to market, cost-effective, and reliable, and it will deliver life-cycle performance exactly as desired and virtually substantiated.

Vision for Preferences & Objectives

Customers and contractors will interface in a high-fidelity immersive simulation environment to define product goals and objectives, explore solution options, understand the impacts of choices, and create conceptual designs that can be developed with complete confidence of technical, cost, and schedule performance.

In the future, M&S systems will assist all stakeholders in assessing what can be done, defining the options, evaluating the cost in dollars, time, and performance, and reaching agreement on the best balance. Customer preferences and objectives will be refined to provide requirements and specifications that repre-

sent the very best balance of business and performance alternatives. This will be accomplished in a flexible framework where the customer has full visual and analytical support to provide awareness of the impact of choices. This environment will support continuous and iterative change, perform optimization of single or multiple parameters, communicate with all stakeholders, characterize uncertainty, and interpret preferences for capture of the requirements and specifications. The result will be a conceptual product on which all parties agree, and which can be designed, built, delivered, and supported within the defined cost and schedule with clearly defined levels of risk.

To put this capability into a use scenario, future product designs may begin with the customer immersed in a visual and mathematically accurate simulation environment where product options can be selected and evaluated with full tactile capability. The customer will receive a complete and accurate account of the result of any selections, in terms of both performance of the product and impacts to cost and delivery schedule. The accumulated selections will be captured in a standard format and utilized to create the initial product model that will drive the subsequent detailed design activities.

Goals & Requirements for Preferences & Objectives

- **Goal 1: Flexible Framework for Capture of Preferences** – Develop a flexible framework that supports communication with the customer to assure the capture of the true preferences. (S)[12]

  – **Standard Formats for Preference Selection** – Develop standard formats for capturing and communicating product preferences.

  – **Automated User Interfaces** – Provide automatically generated customer user interfaces (graphical user interfaces – GUIs) to configure an interaction environment that satisfies the needs of the customer.

  – **Knowledge-Assisted Evaluation Criteria** – Develop knowledge-assisted systems for establishing priorities and metrics for creation of evaluation criteria.

  – **User Profiles** – Develop systems to provide an automated, customer user interface that understands customer profiles and refines preferences.

- **Goal 2: Real-Time Evaluation of Alternatives** – Provide "virtual cockpits" – suites of integrated modeling and simulation tools – that allow the exploration of business and technical options in real time to deliver the best alternatives. (M)

  – **Domain-Specific Toolset** – Define the critical modeling and simulation toolset that must be supported for evaluation of products and components within a selected domain with definable boundaries.

  – **Real-Time Evaluation of Alternatives** – Develop interoperable suites of M&S tools that operate in real time to evaluate all important aspects of product parameter selection.

  – **Assistance in Using M&S Tools** – Develop user interfaces that support the launch of the toolset – freeing the user of the necessity of expert skills in M&S.

- **Goal 3: Decision Support for Trade-offs** – Provide decision support tools that assist the user in the evaluation of multiple alternatives in an environment that involves complex tradeoffs. (M)

  – **Strategies for Decision Making** – Evaluate present requirements management and product design systems to determine best strategies for decision-making.

  – **Balanced Decision Systems** – Design alternative systems that balance the need for fast and intuitive evaluation of options against the need for mathematical rigor in optimization.

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[12] Each of the M&S Goals includes a rough approximation of the time required for its attainment, given as (S), (M), (L) or combination thereof, representing short (3-5 years), medium (5-10 years), and long (10-15+ years) timeframes.

– **Decision Support Toolset –** Provide robust decision support tools that operate with the virtual cockpits to assure selection of best alternatives.

- **Goal 4: Integrated Product Preferences Evaluation & Selection –** Integrate all aspects of product preference in the selection process, including business and operational aspects that may be beyond the visibility of the users – including manufacturability, risk, liability, safety and environmental issues, and uncertainty. (M-L)

  – **Producibility Assessment –** Integrate preference evaluation tools with the ability to select and evaluate processes to assure the manufacturability of any conceived product (this requirement shouldn't be viewed as an elimination of creative ideas – only an awareness of level of capability).

  – **Risk & Liability Assessment –** Integrate risk and liability assessment tools into the virtual cockpits and decision support systems.

  – **Safety & Environmental Issues Assessment –** Develop automated tools for assessing safety and environmental issues and advising the user in their design implications.

  – **Uncertainty in Preference Evaluation –** Develop modeling and simulation tools that address uncertainty in their evaluations, and methods for including an integrated view of uncertainty in preference evaluation.

- **Goal 5: Creation of Conceptual Designs –** Develop systems that refine preferences to create "digital specifications" capable of driving the creation of initial conceptual designs.

  – **Product Specification Standards –** Develop standards for communicating product specifications that are consistent with the parameters, attributes, and features on which designs can be based.

  – **Conceptual Designs –** Utilizing the output of the decision support systems and the virtual cockpits, create a capability to refine preferences to product specifications, delivered in a standard format to create initial conceptual designs.

- **Goal 6: Assessment of Business Attributes –** Develop systems that enable assessment of marketability/fundability based on demand utilizing product and process attributes.

Vision for Visualization/Representation & Product Definition

Future product models and simulations will be high-fidelity, mathematically accurate representations that exactly mirror the real-world product or process and contain or link to all data required to drive design and manufacturing processes.

In the future, product models will no longer be simple physical representations coupled to a database of dimensions and other physical attributes. Instead, the product model will be a complete virtual product, containing and linking to all information related to its manufacture, performance, use, and life-cycle support.

The major change in visualization and representation of product from today's capabilities relates to completeness and usability. Today's environment, in which visualization is focused on conveying a concept, will be augmented by complete and accurate linkage to supporting data. This will enable integration of visualization with parameter selection that supports virtual prototyping and automated/interactive design creation. Scenario-based visualization systems will enable comprehensive evaluation of options and accurate bounding of uncertainty and risk that enable selection of the best alternatives for every product or process attribute.

Product definition will be far more than mere geometry. Product data will be represented in a hierarchical structure that enables automated generation of models for any purpose from the master product object model. The product model will possess (via embedding or linking) sufficient information to drive all

analytical applications and manufacturing applications. Further, it will support the ability to create abstractions for specific applications. Designers will be able to call up customized views of any product or process information to any level of detail, with the custom abstraction automatically generated in real time by the M&S environment based on menus of typical views.

Self-analytical functions will help models build and validate themselves automatically. Specification of a particular material of construction, for example, will cause the product model to automatically link to the enterprise knowledge base and "call up" the archived, validated model of the subject material, including physical properties and associated chemistry and physics data. The model will verify the material selected against the defined performance requirements and alert the designer to any potential problems, offering alternatives for improved performance or reduced cost based on electronically captured design guidelines.

Goals & Requirements for Visualization/Representation & Product Definition

- **Goal 1: Interactive Design Creation** – Develop direct interaction visualization and representation systems that produce the complete product representation including form and function. (M)

  – **Human Engagement in Design Selections** – Provide interaction systems that allow humans to interact directly with design systems making choices, evaluating alternatives, and creating detailed product models automatically.

  – **Visualization & Virtual Prototypes** – Augment the model generation process with visualization tools and virtual prototypes while assuring the mathematical integrity and usability of the generated models.

  – **Product Model Fluidity** – Product models will be "living entities" that understand how enterprise data affects them. They will automatically respond appropriately when changes to the enterprise affect them.

- **Goal 2: Intuitive Modeling Systems** – Provide intuitive systems that are compatible with the human decision process and enable effective interaction with modeling systems. (M-L)

  – **Real-Time User Interaction** – Develop tools for real-time user interaction with rich virtual environments.

  – **Ergonomically Accurate Modeling Environment** – Provide tools that allow human interaction with products and services in interactive and ergonomically accurate environment.

  – **Direct Interaction With the Product** – Provide web accessible digital mockups of products and collaborative visualization systems that allow the user or potential customer to interact with the product.

- **Goal 3: Automated Abstraction** – Develop techniques to support the automated generation, use, and management of models with multiple levels of abstraction. (M)

  – **Standard Product Representation for Complete Communication** – Provide standards for product representation that support all applications from a single and complete model.

  – **Automated Analytical Models** – Provide automated systems that access the information contained in a CAD model and produce mathematically accurate models tailored to any and all analytical applications. The models will be complete including boundary conditions, loads, properties, constraints, etc.

  – **Automated Business Models** – Provide automated abstractions that support all business functions such as costing and life-cycle modeling.

  – **Abstraction for Multi-Disciplinary Applications** – Provide abstraction capability to multidisciplinary applications.

- **Uncertainty Pedigree With Abstractions** – Associate uncertainty with the "master model" from which abstractions are generated, and provide the capability to flow that uncertainty evaluation through all abstractions.

- **Models with Semantic Understanding** – Develop models with semantic protocols to assure reuse across perspectives and at different levels of abstractions without having to repopulate models.

- **Goal 4: Object-Oriented Models for Assured Interoperability** – Develop an object-driven data representation from which models are generated and a supporting engineering ontology, assuring interoperability and reuse. (S-M)

  - **Unambiguous Communication of Design Intent** – Develop open architecture interfaces with CAD systems that enable clear and unambiguous communication of all design intent.

  - **Feature Definitions for Design & Manufacturing** – Define features definitions for design and manufacturing objects, including parametric definitions.

  - **Data Structure for Multiple Levels of Information Communication** – Develop a hierarchical data structure that assures that the level of information, at the needed level of fidelity, is communicated.

  - **Standards for Ontology Development** – Develop standards that support the development of a comprehensive engineering ontology that is automatically updated and maintained.

  - **Data Support for all Models** – Assure the capability to support the multiplicity of models and applications from the common data schema.

- **Goal 5: Intelligent Modeling** – Create an intelligent modeling capability that allows the iterative development of integrated models that function directly from a common object product model and communicate based on a semantic understanding. (M-L)

  - **Mapping of Data & Information Across Domains** – Develop a heterogeneous open-architecture environment that can map (communicate data and intent) across all domains.

  - **Life-Cycle & Multidisciplinary Applications** – Implement the learning, semantic-based system for cradle to grave applications including operational analysis, mechanical systems, variability, electrical, manufacturing, etc.

  - **Complete Communication of Model Information** – Develop the capability to create product model "objects" that capture and communicate all relevant information about the model.

Vision for Product Performance

Future M&S applications will facilitate multivariate analysis to accurately predict how a product will behave in its operating environment, and how it will react to external forces and changing conditions. These next-generation systems will enable rapid optimization of all performance attributes, including reliability, maintainability, business drivers, and other life-cycle factors.

Advanced M&S systems will enable elimination of all but the most critical physical testing, such as for weapons and other safety-critical products, greatly reducing the time and cost of moving products from concept to production. While product testing will not disappear, it will be used only where physical validation is specifically required. In those cases, M&S will augment the value of physical testing to provide complete understanding and assurance of results.

Performance modeling will include all factors that impact performance. For example, products will be evaluated for technical performance as well as for satisfaction of business drivers. The robustness of the

design, including the robustness in the face of uncertainty of process and product performance, will be accurately evaluated.

While manufacturing process capability is usually not considered in product performance evaluation, it must not be overlooked. The ability of a product to perform is inseparable from the ability to make a product compatible with the design intent. Therefore, the ability of an integrated process stream to consistently produce good product will always be considered in performance evaluation.

Automated design systems will assist in the creation of robust designs. Performance modeling applications will run in the background as options are being selected, providing a continuous assessment of performance attributes vs. customer requirements and desires. Advisory systems will offer suggestions based on user profiles that balance objectives. The resulting designs will be optimized for best performance the first time and every time.

This robust performance modeling capability will be enabled through the development, validation, and sharing of new generations of modular analytical codes that draw on distributed enterprise computing assets as need to provide real-time or near-real-time results. Validated performance models of standard materials and components will be shared across industry. Such models will also be a required deliverable of any government contract, facilitating use by all members of the product's supply chain.

Goals & Requirements for Product Performance

- **Goal 1: Pervasive Modeling for Performance Assessment** – Achieve acceptance of product modeling as an adequate method of product performance assessment and assurance and as an augmentation to physical testing. (S)

  – **Compatibility of Model & Test Methods** – Validate performance of product models and assure compatibility with testing methods.

  – **Compatibility of Model & Test Data** – Develop and assure compatibility between modeling data and testing data.

- **Goal 2: Business Value Focus in Performance Modeling** – Establish customer-centric, preference-based definition of business value and implementation in modeling and simulation systems. (M)

  – **Customer Preferences to Design Metrics** – Create tools that convert customer preferences into concrete business metrics.

  – **Business Metrics Included in Performance Models** – Incorporate business metrics in performance modeling systems.

- **Goal 3: Robustness Evaluation** – Develop performance-modeling systems that understand the sensitivities of the design, quantify uncertainties, and define the robustness of product solutions. (M)

  – **Robustness Standards** – Develop standards for determination and communication of design robustness.

  – **Understanding of Uncertainty in Models** – Develop mathematical understanding of uncertainty in product design.

  – **Variation Sensitivity** – Quantify the sensitivity of product's performance to variation in common design parameters.

  – **Robustness Advisors** – Develop knowledge–based design advisors to provide sensitivity and robustness evaluation.

- **Goal 4: Enterprise & Process Capability Inclusion in Performance Assessment** – Extend performance modeling to include an evaluation of the ability of the enterprise to produce products and the ability of the control systems to maintain and assure product quality.[13] (M-L).

  – **Integrated Process Modeling –** Provide an integrated process modeling environment – across manufacturing processes.

  – **Process Control to Assure Product Quality –** Integrate process models with control models to assure in control processes and understanding of control limits.

  – **Process Capability Included in Product Performance –** Establish the capability to evaluate product performance with respect to the inherent capabilities and limitations of the processes available to support the product's manufacture.

- **Goal 5: Performance-Based Design –** Develop and implement performance-based design methodologies. (S-L)

  – **Performance-Based Conceptualization –** Incorporate performance evaluation in conceptualization tools.

  – **Automated Performance Analysis – Operating in the Background –** Develop design systems that operate with performance models in the background, providing an on-screen evaluation of performance assurance and highlighting choices that may enhance performance.

Vision for System Integration & Interoperability

Future product and process models will be seamlessly interoperable, able to automatically plug together to create metamodels of unlimited complexity through a combination of robust standards and self-healing integration capability.

Future models will be transparently compatible, able to plug-and-play via self-describing interfaces, and require no outlay of resources for integration or tuning. Every product and process model will understand its own behavior, its own input needs, and its own output capabilities, such that when a new element is added to the system, it will negotiate with the models of all other elements of the system to "fit in" without human assistance.

The master product model object will contain or link to all of the information necessary to fully identify the product and support all analytical and operational requirements. Each layer of the model will contain adequate and sufficient information necessary to support a specific application or set of applications. Industry-wide standards for integration and interoperability of models and simulations will enable any product model to be "rolled in" to a higher-level model and take its place in an assembly or in a system of systems. The system-level model is the top layer, providing a complete representation of product information sufficient for all enterprise needs.

Interoperability, one of today's largest barriers, is tomorrow's key enabler. Models of all types – product, process, enterprise, control, etc. – will operate seamlessly in a plug-and-play environment. Common languages, self integrating systems, and semantic understanding will all be components of a solution that eliminates translation, reentry of data, and any investment in resolving incompatibility. The result will support totally integrated model-based design and manufacturing systems, from concept definition to life-cycle operation.

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[13] This is covered in the Manufacturing Processes section, but must be considered in product performance.

Goals & Requirements for System Integration & Interoperability

- **Goal 1: Systems Level Product Model -**Provide a systems-level modeling capability whereby a single product representation captures all levels of product information (e.g., peeling an onion) to provide a decomposable model that contains all information needed to support all modeling applications. (M-L)

  - **Continuous Static Representation –** Develop the capability to create models that use STEP continuous static representation.[14]

  - **Composable Single Object Models –** Develop the capability to create single object models that can be combined to build complex product designs.

  - **Interactive Product Model Objects –** Develop the capability to create models that understand their own attributes and can interact with other model objects to understand a resulting superset of attributes, relationships, and behaviors.

  - **Semantic Understanding –** Develop common semantics for representation of features (product, process, etc.) whereby a common understanding is conveyed regardless of context; e.g., a slot is a slot and a weld is a weld – in a context rich environment.

- **Goal 2: Seamless Interoperability of Product Models –** Provide a seamlessly integrated environment supporting plug-and-play functionality of all components of systems level product models. (M-L)

  - **Plug & Play Modeling Framework –** Develop a modeling environment equivalent of a plug-and-play backplane.

  - **Simulation Data Hooks –** Develop techniques for making simulation factors, elements, requirements, and other data inputs readily available and seamlessly integratable into product models.

  - **Complex Object Representations –** Develop the capability to create object representations for product, process, and enterprise that interact seamlessly with models.

  - **Transparent Features –** Develop the capability to cut and paste features from one domain to another and from one model to another, conveying complete understanding of the attributes of the feature.

Vision for Acquisition & Life-Cycle Costing

In the future, acquisition will be model-enabled for all major purchases, and modeling and simulation will be a key enabler of electronic commerce. In the most desirable future, customers will provide preferences, and customers and suppliers will engage in a model-assisted exploration. Preferences will become specifications; specifications will become concepts, and concepts will become automated designs, optimized for life-cycle performance. It should be noted that this vision does carry a threat as well as a potential for good. If simulation-based acquisition (SBA) is used as a one-way tool for the customer to optimize for short-term cost savings, the consequences will be disastrous. If these tools are used to create balanced solutions, good will prevail.

In support of SBA, infinitely scalable product models will accurately, efficiently, and instantaneously calculate the life-cycle cost of ownership. The cost modeling systems will draw from shared cost models and intelligent costing systems that allow dynamic calculation of projected costs based on product selections. The cost basis will be updated as processes are executed, life-cycle costs are accrued, and other factors provide a clearer view of the total cost picture. The ability to project life-cycle costs, augmented by a rich feedback environment, will make these costs much easier to accurately predict.

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[14] Standard for Exchange of Product Model Data (STEP) is an ISO standards project to develop mechanisms for representation and exchange of product models in a neutral form.

Goals & Requirements for Acquisition & Life-Cycle Costing

- **Goal 1: Stepwise Approach to Simulation-Based Acquisition –** Implement systems that enable a system of acquisition based on modeling and simulation and including, consistent with DoD strategies: 1) **Synthesis** of concept or component alternatives; 2) **Prediction** of suitable performance or cost metric; 3) **Evaluation** of alternative solutions (performance and affordability); and 4) **Optimization** in system trade space (performance and affordability). (S-M)[15]

- **Goal 2: Shared & Available Cost Models –** Provide generic cost models, based on features, attributes, and constraints, that are shared for ready access by communities of users. (S-M)

  - **Standard Cost Modeling Framework –** Develop a structure for collecting and managing cost data, information, and knowledge in a shared repository.

  - **Accurate Cost Models–** Develop suites of generic, interoperable cost models for common product types at the material, component/part, subassembly, and systems levels.

- **Goal 3: Intelligent Cost Models –** Develop adaptive cost modeling techniques that automatically and accurately calculate and distribute the effects of a change in one cost parameter across the entire cost model and automatically triggers updates across all affected models. (M)

  - **Automated Cost Modeling–** Develop models that automatically compute the effects of a cost change on the component, subsystem, or system.

  - **Dynamic Change Control for Enterprise-Level Cost Information –** Develop systems that dynamically update all cost data models from cost sources across the enterprise, including integration of new cost data and its impact on all components, subsystems, systems, and activities.

- **Goal 4: Automated Cost Models –** Provide the capability to automatically collect cost data from operations and update cost models in real time. (M)

  - **Enterprise-Level Cost Data –** Provide enterprise-wide sensing and monitoring systems to collect operational information, extract cost information, and automatically update cost models.

  - **Design Versus As-Built Costing –** Utilize operational and performance information to determine as-built cost versus designed cost projections and update cost models to reflect real costs.

- **Goal 5: Life-Cycle Cost Modeling –** Provide accurate systems to analyze products to determine probabilities of failures and forecast life-cycle costs. (M-L)

  - **Dynamic Life-Cycle Models –** Utilize dynamic cost models to accurately deliver life-cycle cost estimates early in the design process and learn from experiential data.

Vision for Validation, Certification, & Uncertainty

Future models and simulations will leverage an increasing base of scientific knowledge to assure accuracy and meet standards for validation and certification. Independent automated analytical applications will analyze models and simulations to accurately define the bounds of their uncertainty, giving designers and decision-makers a clear understanding of risks in extending models into new regimes.

The vision for validation, certification, and uncertainty has two aspects. In the ideal sense, the goal is to build scientific and mathematical rigor and fidelity into models and simulations to the extent that separate validation is no longer needed. "Certification by pedigree" will enable complex models and simulations to be quickly built from a base of validated constituent models, drastically reducing the time and cost of model/simulation development.
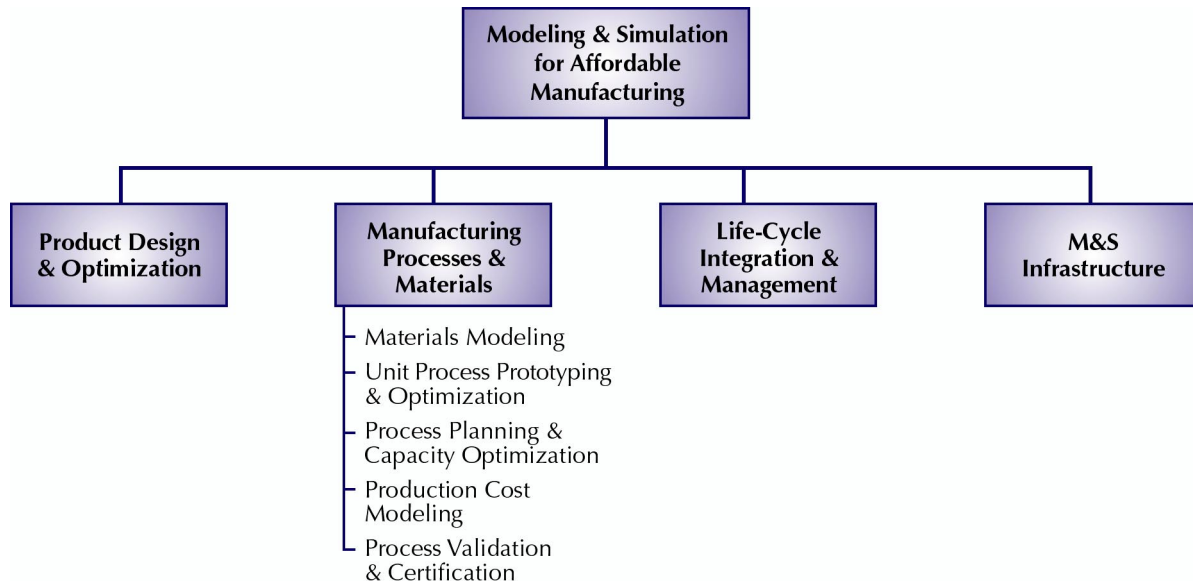
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[15] http://www.msiac.dmso.mil/sba_documents/environm-2.doc.

The near-term step to this ultimate vision is that a rich suite of independently validated, certified, and characterized models will provide complete coverage of the needs of the design community. The models will be accurate and reliable, addressing all factors – scientific, business-related, and human-influenced. The models will be adequate to assess the impact of all factors and make accurate predictions. A thorough understanding of uncertainty and its effect on every model will be quantified. Validated models will be integrated as "systems" to enable evaluation of all alternatives and a full understanding of the results of component and system performance.

Goals & Requirements for Validation, Certification, & Uncertainty

- **Goal 1: Quantification of Bounds of Validation** – Improve tolerancing and uncertainty modeling to allow the establishment of accurate bounds of accuracy, and hence validation requirements, for models. (M-L)

- **Goal 2: Eliminate Need for Separate Model Validation** – Establish a solid science and mathematical basis for M&S, including the inclusion of accepted bounds of uncertainty, to the extent that the necessity for separate model validation is eliminated. (L)

- **Goal 3: Certification by Pedigree** – Establish a capability to certify models by association with validated higher- or lower-level models, assuring the validity of a model through documentation of the pedigree of models on which it is built. (M)

4.0 MANUFACTURING PROCESSES & MATERIALS

ELEMENT DEFINITIONS	
Materials Modeling	Includes all aspects of M&S related to capture, representation (both visual and mathematical), design, manipulation, and addition of material properties, including hardness, ductility, malleability, conductivity, crystalline structure, viscosity, reactivity, porosity, resistivity, conductivity, and similar attributes.
Unit Process Prototyping & Optimization	Includes all aspects of M&S related to evaluation of effectiveness, quality, and efficiency of a new or modified manufacturing process, and tailoring to realize the best process results within defined parameters. Includes manufacturability aspects such as material selection, part and feature complexity, tolerances, assembly, assembly interfaces, processing of materials (e.g., casting, forming, machining, composite fabrication, electronics fabrication), and similar factors.
Process Planning & Capacity Optimization	Includes all aspects of M&S related to evaluation of multiple interrelated manufacturing processes intended to produce single or multiple products, and tailoring to achieve the best results (cost, quality, throughput, and time) for the total manufacturing activity (includes OEM and supplier).
Production Cost Modeling	Includes all aspects of M&S related to the determination, prediction, and optimization of the cost of manufacturing a product given a definition of the product and its manufacturing processes.
Process Validation & Certification	Includes all aspects of M&S related to assuring that a manufacturing process or processes will perform consistently and reliably in accordance with the design intent and specifications.

4.1 CURRENT STATE ASSESSMENT FOR MANUFACTURING PROCESSES & MATERIALS

As noted in Table 4-1, modeling and simulation for manufacturing processes and materials is currently not on the critical path for most applications. Models of processes are often created to help diagnose a problem, but rarely are used to create and optimize process designs. The up-front investment required to enable M&S-based process development and material planning is a major barrier, as manufacturers continue to focus on short-term cost equations instead of life-cycle value. Government investment in this area has been lacking for similar reasons. Additionally, current regulations requiring empirical certification bar manufacturers from realizing gains that might be made through M&S.

In areas where M&S is being applied, the results have been positive. M&S tools are delivering excellent returns on investment in areas such as forging and spin forming, supporting creation of complex net shapes with processes and materials optimized for performance and cost-effectiveness (Figure 4-1). M&S-based tools for mold design, pour, solidification, and defect prediction in development of complex investment castings has enabled significant improvements in mold optimization and product yield.

The lack of awareness and confidence in process modeling and simulation tools makes it difficult to secure support for application development efforts with potentially large payoffs in time, resources, and profitability. A good example of such impact is materials failure, where fatal flaws that might have been found through process and product simulation are discovered long after tooling is in place, production lines are committed, and the product is in the field.

Integration and interoperability of modeling and simulation tools is sorely lacking in the process realm. Most M&S tools are single-function applications. They may deal with the stress and temperature profiles of products undergoing individual processes, but seldom do they deal with the total performance profiles of products and processes across multiple operations, and even less frequently with adaptive, interactive, real-time optimization of multiple product and process parameters. Attempts at improving the interoperability of process M&S tools have been frustrated by inadequate data representations as well as incompatible data structures and representation formats. Rich standards do not exist or are not widely used for representing and manipulating process parameters. There are no incentives for suppliers to invest in M&S to interact with preliminary designs.

No good standards exist to ensure compatibility and commonality between process modeling and simulation tools and the rest of the systems that support the global manufacturing environment. Currently, integration and optimization of capacity is difficult in a globally distributed supply base. Factors contributing to this condition include proprietary information concerns, adversarial OEM/supplier relationships caused by a low trust factor, and the lack of cost visibility across the supply chain.

Industry lacks collaboration strategies to solve these basic issues, and export control regulations impose additional restrictions (particularly in the aerospace/defense sector) on sharing of product and process information throughout a global supply chain.
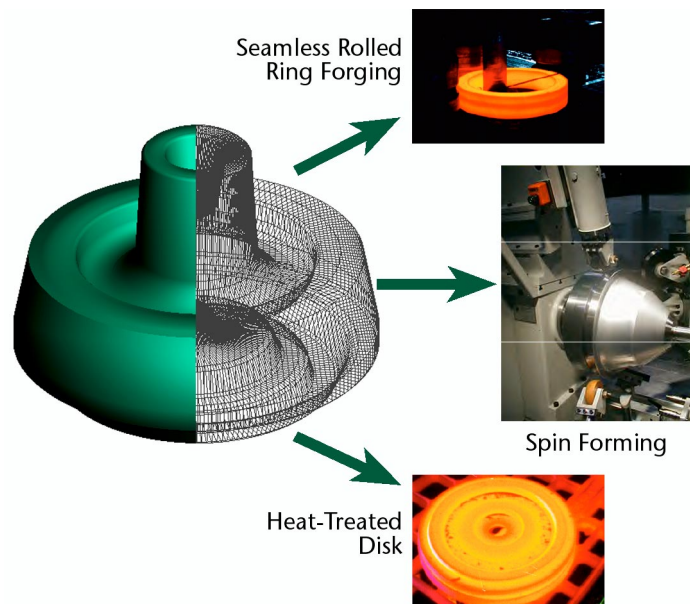

Figure 4-1. Advancing capabilities to model fabrication techniques are opening up new process options, enabling creation of highly precise net shapes for complex products.

Table 4-1. State Map for Manufacturing Processes & Materials

Sub-Element	Lagging Examples	State of Practice	State of Art/ Best Practice
Materials Modeling	• Many industries do not model materials during the manufacturing process • Companies not using off-the-shelf materials databases • Materials and processes are a decade behind design tools • Material development time exceeds the product cycle by a factor of 2 • Process models of functionally graded materials are limited	• Independent modeling capabilities at various scales but not linked • Companies using own proprietary data – don't share with suppliers • Complexity of M&S is much higher for material and processes	• Accelerated insertion of materials – AIM program (DARPA) • Continuum of micro to macro modeling (RPI) • Functionally graded materials modeling for metals
Unit Process Prototyping & Optimization	• Some build no prototypes of products • Data behind product life-cycle management (PLM) tools is lagging • Dual use technology is inhibited by government regulations • Not common specifications and processes across OEMs inhibiting more pervasive M&S tools	• Use stereolithography modeling • Use modeling and simulation on an optional basis • High reliance on product data management (PDM) applications; PLM just beginning to be available • PDM • Cost issues are being considered in materials selection for limited applications	• Virtual modeling for specific components in complex products (P&G) • Demonstration of PDM tools managing total breadth of product and process development at P&G
Process Planning & Capacity Optimization	• Lack of robust process planning tools	• When to model is not known in the life-cycle • More ad-hoc modeling • Business processes are taking advantage of process management tools, but technical community is not • Lack of common specifications affects ability to optimize facilities • Manual extraction of design data to drive process M&S	• Automotive has templates to determine when modeling should occur (GM) • Modeling is a structured product development process (GM) • Common practices and specifications
Production Cost Modeling	• No robust, interoperable, or verifiable cost models available	• Little sharing of cost data across supply base • No ISO standard • No ability to capture requirements in a virtual enterprise • Current accounting systems don't capture cost • Use accounting-based costing	• Model cost based on way company is set up financially (Activity Based Costing) (Rockwell)

Sub-Element	Lagging Examples	State of Practice	State of Art/ Best Practice
Process Validation & Certification	• Six Sigma philosophy not widespread in modeling development • Don't have standards for on-machine probing • Little understanding of verification/ validation processes for physics-based simulations • Validation is done after decision process is complete	• Widespread use of Six Sigma in manufacturing processes • Use of on-machine verification with probes • Crash analysis used in design process – validation process with sub models (expending resources in a high liability area) • Proving with previous tests that design is valid • Extensive models are being created for limited applications that have high value • Not using M&S tools for re-certification of process changes • No M&S tools to accept process testing • Validation is product based	• Using emulation of PLC logic controllers in simulation environment prior to making product as it applies to the total system (GM) • Using process model to make internal decisions

Materials modeling lacks continuity from nano to macro scales involving some twelve orders of magnitude. This degree of model continuity is necessary to adequately tie materials properties at their most fundamental level to material properties as they apply to processes and products. Some early work that is currently being conducted in this area includes modeling methods, adaptive multiscale methods, and model uncertainty.

Model validation and verification are key needs in the manufacturing environment where modeling and simulation are pervasive. Currently, product validation procedures will not accept process-based validation and verification.

The level of skill in today's workforce is often insufficient for pervasive modeling and simulation in the manufacturing environment. Additional training or easy to use interfaces are needed to facilitate the wide spread usage of modeling and simulation. Additionally, there are currently no strategies for dealing with model uncertainties and the ever-increasing need for additional computational power.

Materials Modeling

The state of practice for material modeling varies widely across industry. Most companies do not model materials to support manufacturing, but rely on known material properties and mature production processes that deliver consistently acceptable results within defined parameters. While this philosophy meets basic business requirements, it closes off potentially rich avenues for innovation and breakthrough improvements in product performance.

Material and process modeling technology lags product modeling technology by a decade or more. Material modeling is far more complex than product modeling, since the issues involved are not related to simple geometry, but rather to chemistry and physics. Many specialized material processes have been modeled by private and academic R&D organizations; however, these models rarely find a path to inclusion in commercial M&S products. Material behavior models are often developed for new manufacturing processes to aid in understanding during development, but these models are typically left behind early in the development cycle. For example, although the aerospace industry has made significant investments in developing material behavior models for metal-matrix composites, few of these models have seen actual product application. Little effort is made to update, enrich, and verify material models based on production results, which limits utility outside their original application.

There is minimal sharing of material models within or across industry sectors. Companies use their own proprietary tools and data to develop material models and simulations (such as constitutive models for behavior of alloys and materials under regimes of processing conditions), but do not share this data with their suppliers or competitors. Standards for material models and simulations are ill defined, effectively barring integration of multiple models outside the framework of the originating M&S application.

The Accelerated Insertion of Materials (AIM) program at DARPA is the most visible initiative currently addressing fundamental materials M&S challenges. AIM seeks to reduce cycle time for development, validation, and insertion of new materials into weapon systems through advanced modeling techniques. AIM is providing a foundation of capability for high-profile materials, alloys, and applications, but broad application of material modeling is viewed as a distant capability. Rensselaer Polytechnic Institute (RPI) has a state-of-the-art program for linking micro material models to macro material models in a continuum, addressing linkage methods, scaling techniques, and model uncertainty. Some work also is being performed on functionally graded material modeling for metals.

Unit Process Prototyping & Optimization

Modeling and simulation has been used in process prototyping and optimization to varying degrees for more than 20 years. Finite element modeling, first in two dimensions and now in three dimensions, has enabled predictions of casting, forming, forging, and other material solidification and deformation processes. In electronics, M&S is used extensively in designing manufacturing processes and optimizing

process operations. Perhaps the strongest use of M&S in process prototyping and optimization is in the continuous-process industries where M&S is in common use for design and optimization of intelligent, controlled processing.

Much of the work in M&S for process design and optimization is taking place in the research environment. For example, NIST and several of the national laboratories have strong programs in M&S for metalworking, ceramics, and chemical processing. Some elite university programs exist, and they are doing good work with industry. For example, the metalworking M&S program at the University of Illinois has been at the fore for several years. Rensselaer Polytechnic Institute has excellent programs in electronics processes. Ohio State, Purdue, and Michigan are also leading centers of research and development in the process modeling community.

Process simulation tools have found their way into routine development of manufacturing processes. Early investments by the Air Force in FEM tools for metal deformation opened the door for the commercial development of several tools for forging applications. Both large and small forging houses today apply some form of PC-based FEM tools to simulate metal flow for closed-die methods. Although 2-D axisymmetric applications are the mainstay, 3-D simulation capabilities for non-symmetric geometries have been validated and implemented.

Investment casting processes are another emerging simulation capability that is being routinely applied, to design complex molds for structural aerospace castings. Simulation of metal flow during mold fill and simulation of solidification has led to greater understanding of casting phenomena. The ability to visualize flow fronts, entrapment of inclusions, and the root cause of shrinkage defects has enabled optimized mold designs to improve quality and yield and shorten development time (Figure 4-2).

Other variants of casting and forging simulation tools are seeing expanded use. Simulation of processes such as sheet-metal forming, stamping, heat treatment, and ring rolling is expanding the base of unit processes that can be assessed through M&S prior to empirical development. There remain, however, significant gaps in a number of key unit processes, and there is no meaningful capability to integrate multiple unit process models into a multi-step tool that can enable early decisions about process options, cost, or optimized utilization of manufacturing assets. There is no mechanism to provide the designer with a "state" of the manufactured part as a starting point to accurately predict part performance during mechanical design analysis activities.

Another deficiency in today's process M&S capabilities is the lack of common data models for representation of geometry, features and attributes, physical states, or other model characteristics. This is an imperative for integration of multiple unit process applications into a multi-step simulation of manufacturing.
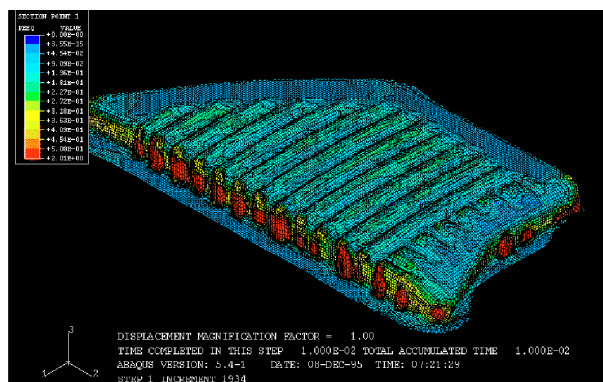
Nozzle Panel Simulation

Completed Part

Figure 4-2. Use of simulation tools to optimize a forming process for precision components helped Pratt & Whitney demonstrate a 6:1 reduction in design-to-manufacturing time.

Cost issues are being considered in material selection for limited applications. Modeling of cost in any manufacturing process is limited in today's current state. Most accounting systems primarily gather data and report at a level far above the part level. Since there is little visibility into cost, the engineering and manufacturing organizations do not include this metric in continuous improvement activities on the shop floor. The manufacturing organization in today's environment has no capability to provide cost feedback to the design process in real time. Typically, 1 to 2 weeks are required to provide the manufacturing cost of a part design.

Although most companies build prototype products, some still do not prototype processes prior to committing capital resources. The regulatory environment often inhibits transition of technology for dual-use applications. The lack of common specifications and processes across OEMs inhibits the creation and use of more pervasive M&S tools.

Process Planning & Capacity Optimization

The state of practice for M&S in process planning and capacity optimization is more ad hoc than systematic. Business processes are taking advantage of process management tools and increasingly sophisticated enterprise resource planning (ERP) applications, but the technical community is not. "Variant" and "generative" computer-aided process planning tools are moving toward integration with computer integrated manufacturing (CIM) environments and CAD geometry (Figure 4-3), but true model-based planning remains a visionary goal. There is currently no effective ability to extract useful data from CAD models to aid in process planning. Even in leading-edge applications, feature details must be manually extracted from CAD models for entry into the process planning system.

The present lack of robust planning tools and standards for process planning greatly limits companies' ability to optimize their facilities. Current modeling practices rely on manual extraction of design data to create process models and simulations. Since these process models are static (i.e., created manually by modeling experts at significant time and expense at a given point in time based on available data), it is difficult to determine the best point in time to create the model in order to get the best results. Meaningful improvements in the time and cost of creating such models, coupled with the ability to continuously update the model based on current data, are essential to realizing a commercially valuable capability

General Motors is a prime example of the state of the art in this area. GM uses templates to determine when modeling should be done, and uses modeling as a key ingredient in its structured product development and planning proc-

Figure 4-3. Generative process planning tools are moving toward integration with CIM environments and CAD geometry, demonstrating the value of sharing information across the different functions of product development.

ess. Other companies use standard practices and specifications in process planning, integration, and capacity planning within their own corporate boundaries and supply chains. However, this kind of rigor is the exception rather than the rule.

The lack of standardized, validated models for unit processes and manufacturing equipment (e.g., machine tools) is another key barrier to model-based process planning. While these kinds of models are being developed in a number of R&D programs, commercial application to date has been limited to solving
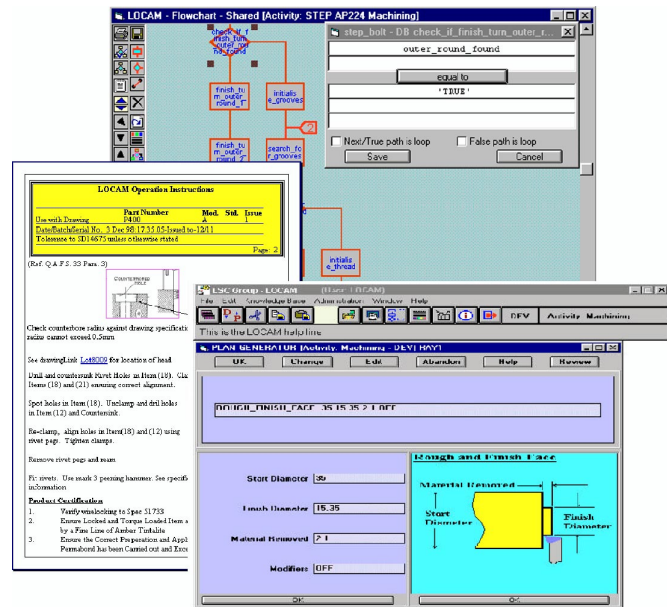
very narrow, process-specific challenges or on demonstration of modeling techniques (notably, 3-D visualization) for further development.

Production Cost Modeling

The current state of practice for production cost modeling is that there are no robust, common cost models available, and interoperability with other enterprise M&S assets is lacking. There is little sharing of cost data across the supply base, and there are no ISO standards for cost models. Such cost models that do exist are simple spreadsheets built by hand by manufacturing engineers, and are accurate only for rough-order-of-magnitude estimating. Accuracy depends largely on the individual engineer's experience with the same or very similar products and processes. Work breakdown structures (WBSs) and bills of material (BOMs) are generated early in the estimating process for a new or modified product as a mechanism to capture all of the anticipated costs, but do little more than provide a structure for paper-based cost models.

Government agencies will on occasion provide an Excel or Lotus 123 cost model as part of a request for proposal to help assure commonality and comparability of different vendors' quotes, but these kinds of models are difficult to apply because different companies collect and account for different types of direct and indirect costs in wildly disparate fashions.

Current accounting systems do not capture detailed manufacturing costs well, especially on a part or component basis. Instead, accounting-based costing is used – which is primarily an information gathering and reporting function. There are few examples of cost forecasting and predictive cost modeling, especially anything that is linked with the product design process. Rockwell is an example of where a company has broken out of the mold to model cost on the way the company is set up financially. Their activity-based costing system has made great strides toward integration of cost models and manufacturing models.

Process Validation & Certification

The current state of practice for process validation and certification includes the widespread use of Six Sigma or similar methods of reducing defects and variation in manufacturing processes, especially at the larger original equipment manufacturers (OEMs) and at the larger top-tier suppliers. A few select, lower-tier suppliers have had some Six Sigma training from OEM supplier development teams, but the majority of small manufacturers have not benefited from this trend. Six Sigma has not pervaded the broader "above the shop floor" business functions in most manufacturing enterprises. The role of modeling and simulation tools in the verification and validation of processes is lagging. Physical testing and post-operation verification is the norm. There is an increasing use of in-situ verification methods such as on-machine probing; however there is a lack of standards and application is only on select processes and components. M&S tools for verification and validation are emerging; however, they are focused on the product not the manufacturing processes.

M&S tools do not play a significant role in process verification and validation. There is little understanding of verification strategies for physics-based simulations; therefore, there is little use of simulation tools for certification of processes or process changes. The results of process testing have no means to interact with M&S tools to build a data foundation for process certification. There are isolated examples of the power and capability of simulation tools in validation and certification, however these will be used more at the product level than the process level. The automotive industry, for example, is rigorously developing and applying M&S tools for very expensive validation testing such as vehicle crash analysis applied during the design process. Although modeling the entire vehicle is computationally difficult, the application of sub-models for select vehicle components or subsystems is being applied. Since there is a strong business case for understanding this high-liability aspect of the automotive product and the physical testing is very expensive, there is a significant investment being made for the development of M&S

tools for the validation and certification function. The business case to invest in most other applications of M&S tools for validation and certification has not materialized within individual companies.

4.2 FUTURE STATE VISION, GOALS, & REQUIREMENTS FOR MANUFACTURING PROCESSES & MATERIALS

Vision: Manufacturing processes for complex products will be designed, optimized, tested, and qualified entirely in the virtual realm, drawing on a rich base of scientifically accurate and complete models and simulations of materials, unit processes, and manufacturing equipment.

Future manufacturing process designers will draw on a deep library of validated, thoroughly characterized models and simulations of common materials, unit processes, and manufacturing equipment to integrate and optimize process designs for individual products. Equipment and tooling manufacturers and commodity vendors will provide validated 3-D simulation models and supporting data as a basic part of the equipment and products they sell, applying common standards to assure the ability of different vendors' models to integrate accurately in plug-and-play fashion. This will enable process designers across the supply chain to quickly create accurate simulation models of complex product production lines, filling in gaps only as needed for customized, product-specific tooling, fixturing, proprietary processes, and unique process steps such as assembly.

The ability to create valid process models will enable manufacturing process designers to interact fully with the product design team from the inception of the design effort, allowing mutual optimization of product and process designs and manufacturing strategies to arrive at the best combination of performance and cost in all aspects of design and manufacture. Intelligent process design advisors and on-line analytical tools will flag potential issues such as production choke points or problematic tolerances, enabling the production team to design in appropriate margins and develop workaround options to mitigate risks to cost, schedule and quality.

These integrated capabilities will drastically reduce the time and cost of translating product from design to delivered first unit, greatly reducing requirements for process qualification and production certification.

Future State Vision for Materials Modeling

Validated, high-fidelity material models will be shared across industry-wide networks to improve quality, speed, and risk mitigation associated with material and process decisions. Selection of materials in product and process design will be highly automated and optimized based on defined product requirements and goals, with virtual advisors guiding designers to select the material giving the best balance of cost and performance.

The future state vision for materials focuses on an environment where there are no custom translators between tools and there is the ability to access and apply materials models to anywhere the information is needed, and to fully integrate with computer-aided design, engineering, and manufacturing systems. Broad-based frameworks will support compatible, linked materials processing and behavior models to be developed, populated, and applied. Fast computation, enabled by advanced hardware capabilities and software strategies, will enable analysis and creation/development of modified or new materials systems on a reduced time scale. Effective behavioral and characterization models for all materials and processes will enable requirements-driven selection of materials. Materials models will be integrated into a design knowledge base where material selections are made and requirements for new materials systems are synthesized.

Material modeling will be based on a multi-scale perspective where macroscopic behavior, with emergent properties, is simulated on a foundation of microscopic models. The challenges of bridging the gaps and

scales between atomistic and continuum models will be understood such that the requirements-driven selection and creation of materials is enabled using system-level criteria. Mechanistically based material properties and structure models will be able to predict the performance characteristics of design solutions at the component and system level. Materials models will communicate across product analytical codes and multiple scales in the integrated product and process design environment.

Rapid development and insertion of new and modified materials will be an integral part of the product development process. The need for new materials systems will be identified along with the magnitude of time and resources needed for development, characterization/certification, and insertion into the product stream. Development of alloys and other precision-engineered materials systems will be driven by simulation systems able to accurately predict physical, chemical, and electromagnetic interactions at the molecular level.

Goals & Requirements for Materials Modeling[16]

- **Goal 1: Interoperable Framework –** Develop an interoperable framework and interfaces for the integration of validated materials, material processing, and manufacturing models into the virtual product model environment. (S)

    – **Create & Expand Process Models** – Assess the current state and validity of unit process models for all essential materials, material processes, and manufacturing processes and create and expand the population of validated models to fill the gaps based on a prioritized need. Establish the standards for verification and validation of materials and process models.

    – **Unit Process Model Relationships** – Define the relationships, coupling of phenomena, interfaces and linkages, database requirements and sharing, and standards for information representation between materials, material processes, and manufacturing models to enable the integration of a suite of validated tools to achieve multi-model analysis capability with consistency between inter-related physical processes.

    – **Materials Database** – Create the structure for a secure and compatible science-based materials and process database and repository to incorporate materials properties, constitutive properties, behaviors, and material and process attribute data required for supporting simulation, optimization, and analytical analysis. Establish linkages to other certified industry, academic, and government databases. Create the structure for shared access and maintenance and the methods and standards by which data and models are validated.

- **Goal 2: Multi-Scale Continuum Modeling –** Develop technologies to bridge the gaps from macro models to micro models and enable the application of validated multi-scale systems models and integration of materials, material processes, and manufacturing models. (L)

    – **Multi-Scale Linkage Models** – Create linkage and bridging mechanisms, protocols, and models to manage the exchange of data and information within the framework between different levels and layers of scale from micro level (atomistic) to macro levels (continuum). Provide for the consistency of interacting physical phenomena between models.

    – **Multi-Scale Models & Simulations** – Identify high-priority material needs and develop methods to determine when micro-scale modeling is beneficial to high-fidelity process modeling and simulation. Initiate the development of effective material behavior models for critical underlying micro-scale phenomena (such as grain growth and size fractions, dislocations, crystal structure). Provide effective and reliable multi-level simulation tools that manage the linkages and information exchange between levels.

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[16] Each of the M&S Goals includes a rough approximation of the time required for its attainment, given as (S), (M), (L) or combination thereof, representing short (3-5 years), medium (5-10 years), and long (10-15+ years) timeframes.

- **Uncertainty Management** – Create interfaces and basic methodologies for accounting for and tracking the uncertainties associated with materials databases and models across different scales in multi-scale models.

- **Goal 3: Material Selection Requirements Translation –** Develop the methodology and interfaces for a menu-driven material selection advisor model that systematically translates customer desires and design requirements for the selection of materials and various options. (M)

  - **Materials Selection Advisor –** Create a menu-driven materials selection advisor model and user interface that is integrated with the virtual product model and optimization system and is responsive to requirements data and customer preference rules.

  - **Materials Requirements Modeling** – Develop models to extract materials and process requirements from the higher-level modeling of customer desires and preferences, design intent, and product performance goals. Develop methodologies that define design and material requirements and product performance attributes.

  - **Optimization Requirements** – Develop criteria and parameters required to enable material models to interact with integrated process simulations, virtual product models, and system optimization tools.

- **Goal 4: Materials, Processing, & Manufacturing Information Repository –** Create a secure and accessible data repository of validated materials, processing, and manufacturing information that enables easy access by all authorized suppliers and users and provides for maintenance, continuous updating, and certification of data. (S)

  - **Access Methodologies** – Create the formats and methods for dealing with authorized access, protection of proprietary information, maintenance and automated updating, and location issues for common materials and process data repositories. Develop user graphical interfaces and automated linkages for integration into advisors, virtual product simulations, and optimization models.

  - **Data Scope** – Define the scope of materials, processes, manufacturing information, data, and models to be captured in the repository. Assess existing process models, materials data, and manufacturing data that would be appropriate for inclusion from sources such as universities, national labs, consortia, and other industry resources.

  - **Validation Methods** – Develop the standards, specifications, and format criteria to test and validate data, models, and information for accuracy and provide for boundaries and uncertainty constraints.

  - **Shared Material Modeling Repository** – Collect and validate data, models, and information against the established formats and criteria. Populate repository with existing and created data. (L)

- **Goal 5: Material Risk Mitigation Methodologies –** Create methodologies for the identification of uncertainties, variations, and mitigation of risk for the selection and development of new or modified materials. (M)

  - **Identification of Required Properties** – Develop a mechanism for the identification of required and desired material properties based on the translation of customer preference, design intent, and performance requirements. Provide for the identification of sensitivities, boundaries, regimes, and constraints for product application.

  - **Business Case for New Materials** – Develop business case models and templates to quantify and capture measurable benefits, savings, performance, and life-cycle advantages for the development of a new or modified alloy or material system. Establish financial models for interpretation of benefits into business performance metrics.

- **New Material Insertion Plan** – Provide a structured, gated development and deployment plan for new or modified materials that includes critical technical and financial reviews including M&S, testing and characterization, and product insertion and integration.

- **New Material Data Integration** – Integrate validated characterization, behavior, and design allowances data from new or modified materials into existing databases and repositories for interoperable M&S and optimization use.

Future State Vision for Unit Process Prototyping & Optimization

Models and simulations for all manufacturing processes will be integrated into multi-disciplinary optimizations of product designs. Physical prototypes will be replaced with multi-dimensional virtual models that embody the knowledge created in each step of the product development process – from idea generation to detailed design to manufacturing plan and execution.

The vision for unit processes envisions that availability of robust, comprehensive models for all materials and manufacturing processes will enable fast, accurate simulation of any combination of processing steps, with the output integrated into a multi-dimensional virtual simulation model of the evolving product. All attributes of the process, including cost, will be available for inclusion in design optimization at any appropriate level. Robust methods and processes for creating virtual prototypes and process simulations will enable rapid assessment of producibility, resource availability, capacity, and cost. Virtual models will be easily tailored to and compatible with the unique manufacturing operations and assets of any company or of an entire supply chain. These models will be built on standard, interoperable representations of processing equipment. The virtual model, once optimized, will directly output the manufacturing requirements, controls, and codes necessary to produce and verify the product with respect to whatever stream of resources and facilities is defined.

Simulations of materials and manufacturing processes will be integrated into the design optimization engine such that process changes will directly alter product geometry models within defined performance constraints. Materials and processing data will be contained in secure repositories accessible to the design system, material and product suppliers, and enterprise management functions. Process information and knowledge will be integrated into advisory systems that contain the knowledge, rules, constraints, controls, and parameters for optimization, and can initiate simulations or parametric analyses as needed.

Goals & Requirements for Unit Process Prototyping & Optimization

- **Goal 1: Interoperable Models for All Unit Process** – Develop interoperable, accurate unit process models that are validated and maintained and accessible for the integration of materials, materials processing, and manufacturing simulations. (L)

  - **Models for All Processes** – Assess the manufacturing process and materials modeling gaps and define high-priority needs to create and/or expand models for materials, material processes, and manufacturing to enable the virtual design of optimized processes.

  - **Multi-Scale Models** – Develop the technologies and ability to bridge the gaps from macro models to micro models that enable the validated application modeling of multi-scale systems. Develop the technologies and ability for the integration of materials, material processes, and manufacturing models. (L)

  - **Multi-Scale Linkages** – Create linkage models between micro (atomistic) and macro (continuum) levels to enable improved predictive simulations over broader ranges of parameters and conditions.

  - **Accurate Simulation Tools** – Provide effective and reliable simulation tools that accurately reflect the materials and manufacturing processes of interest in a specific company or value stream

across an enterprise, and are verified and validated against standards for certification within known boundaries and parameters.

  – **Tools to Manage Uncertainty** – Create the interfaces with basic science and experimentation methods that enable the management of uncertainty and sensitivities when models with incomplete or preliminary information are applied in an integrated framework.

  – **Model Relationships** – Define the relationships between materials, materials processes, and manufacturing models. Develop the standards and specifications for the integration of models into a framework to enable the simulation of multiple unit processes.

- **Goal 2: Process Selection Requirements** – Develop the methodology and interface for translating requirements and preferences from the higher system level or the individual unit process level in a systematic way to enable the selection of an individual or multiple-unit process for a specified application. (M)

  – **Process Selection Advisor** – Create menu-driven process selection advisor tools that can be accessed manually by engineering or through automated linkages to an integrated system for automated model generation and/or optimization.

  – **Process Requirements Models** – Develop the capability to extract process requirements definition from higher-level models in order to define the relationship between requirements, design characteristics, and process capabilities.

  – **Optimization Models** – Develop the capability to model system optimization requirements and utilize this information as criteria input for the process selection advisor.

  – **Risk Mitigation Methodologies** – Create methodologies for the mitigation of risk and the quantification of uncertainties for the selection of new processes. (S)

- **Goal 3: Materials & Process Repository** – Create a secure repository of validated materials, processing, and manufacturing information available to the design system, engineering, and all raw material and product suppliers. (S)

  – **Baseline Repository** – Create the structure for a secure and compatible science-based materials and process database and repository to incorporate materials properties, constitutive properties, behaviors, and material and process attribute data required for supporting simulations, optimization, and analytical analysis. Establish linkages to other certified industry, academic, and government databases. Create the structure for shared access and maintenance and the methods and standards by which data and models are validated.

  – **Security & Maintenance** – Create the methodology for authorizing access to select information, protection of supplier-owned or proprietary information, maintenance strategies, and host location issues for common repositories.

  – **Data Scope** – Define the scope of data, attributes, models, and other information required to support integrated functionality to be captured in the repository. Develop the standards and specifications for storing and identifying verified, validated, and certified data and models as well as preliminary data and models.

  – **Populate Repository** – Populate the repository with existing data and establish maintenance responsibilities and the determination of the quality of existing data initially populated. Populate the repository with new data and models per the established certification criteria.

- **Goal 4: Process Capability Tools** – Create tools to evaluate process capabilities to determine characteristics such as producibility of features, resource capabilities, and process repeatability within known boundaries of process parameters and conditions. (S)

- **Models for All Processes** – Conduct gap analyses and define a hierarchical plan for developing verified and certified models for all high-priority (based on industry weighting) materials and manufacturing processes.

- **Multi-Level Interoperable Process Models** – Create interoperable models that capture overall process performance characteristics across levels of detail from a unit process to a plant or enterprise level.

- **Interoperability Standards** – Develop the standards and specifications for the creation of interoperable models that can be easily integrated (plug and play) with multi-code analysis and optimization tools.

- **Designer Knowledge Base** – Develop a secure knowledge base of verified and certified materials and manufacturing process data, attributes, and models that is accessible by the designer and design advisor tools.

- **Knowledge Base Maintenance** – Develop methodology and access authority for populating, updating, maintaining, and extending designer knowledge bases.

- **Goal 5: Mature & Expand Existing Simulation Technologies** – Mature and expand the capabilities of existing science-based simulation technologies to facilitate use by a wider base of manufacturing engineering practitioners. Make underlying numerical technologies more transparent to the user. (S)

  - **Robust Automation** – Introduce improved user interfaces and develop robust automation for the numerical aspects of simulations to enable broader user capability and standard methods to facilitate integration into product models.

  - **Define & Fill Gaps** – Assess existing process-simulation tools and identify significant or high need processes that lack robust simulation capabilities. Define projects and collaborations to develop or extend software platforms to fill in gaps.

  - **Expand Databases** – Expand the availability of constitutive databases to include all processes that are simulated and cover the full range of processing parameters possible for the existing and envisioned materials and manufacturing processes.

  - **Demonstrate & Document Successes** – Define success criteria and conduct verifications and accuracy simulation trials to expand confidence in simulation results. Develop the standards and criteria to "certify" models and simulation tools for capability and robustness within a given scope of boundary conditions and parameters.

  - **Product Model Interfaces** – Define the standards and specifications for the interfaces, linkages, and interaction of process simulation tools with product and optimization models, design advisors, and other analysis capabilities.

- **Goal 6: Materials/Processes Advisors** – Create process advisors for individual materials and manufacturing processes to be used by a variety of engineering and design functions. (M)

  - **Existing Process Rules** – Develop and apply the methodology to capture knowledge and develop rule sets for existing materials and manufacturing processes, provide access to published guides, handbooks, and other pertinent industry reference data.

  - **Science-Based Simulations** – Incorporate science-based materials and manufacturing process simulations and algorithms (from Goal 5 above) into advisors to support early analysis and decision-making during conceptual product definition.

  - **Optimization Parameters** – Develop optimization elements and parameters for integration of advisors into multi-code analyses and virtual product models.

Future State Vision for Process Planning & Capacity Optimization

Total manufacturing activity will be optimized using product-driven enterprise modeling and control based on demand and business performance metrics.

The future state for process planning and capacity optimization will leverage the existence of fully modeled facilities that are modular and designed for easy reconfiguration in response to business demands and opportunities. Enterprise process and equipment assets will be inherently flexible, enabling rapid response to changes in business markets and demand signals. The capacity to perform work throughout the enterprise will be modeled such that work forecasting and allocation automatically optimize asset utilization and resource productivity.

Manufacturing process plans will be automatically generated based on product requirements as the product design evolves, with direct linkages to capacity models and enterprise models enabling proactive resource planning and allocation. The enterprise will rapidly tailor capability and capacity by adding or removing supplier assets through pre-negotiated business relationships, enabled by integrated supply chain business systems and industry-wide standardized, streamlined accounting practices. Advisory tools linked to the enterprise knowledge base will guide managers in optimizing capacity requirements and utilization during the early process planning and manufacturing execution stages of producing product.

The future workforce will be equipped with the knowledge, skills, and corporate culture to support a fluid enterprise environment. Typical compartmentalized job classifications will give way to multi-skilled workers that can respond to frequent changes driven by small lot sizes, reconfiguration of enterprise assets, and fluctuations typical of short cycle times and fast-to-market pressures. Workforce training and certification will be directly accessible through the normal workplace computing interfaces as well as through training capabilities embedded into the enterprise's system

Goals, & Requirements for Process Planning & Capacity Optimization

- **Goal 1: Automated Model-Based Process Planning** – Create tools to generate an optimized process plan for manufacturing operations based on interaction of process and enterprise models with the product model. (S)

  – **Process Planning Data Standards** – Develop data standards for all materials and manufacturing processes and equipment to enable broad utilization and integration of data into multi-functional models and tools.

  – **Validated Process & Equipment Models** – Develop and maintain an industry-wide shared repository of validated, well-characterized models and simulations for all processes and equipment based on industry priorities and value to multiple industry sectors.

  – **Automated Knowledge-Based Process Planning** – Develop the capability for automated generation of knowledge-based process plans for diverse materials and manufacturing processes as an output function of the optimization function in the master product model.

  – **Process Labor Standards Libraries** – Develop and maintain a library and database of labor standards for all direct and indirect materials and manufacturing processes and functions in the enterprise for integration into resource and process planning models and optimization systems.

  – **Process Cost Feedback Mechanisms** – Establish standards and mechanisms for real-time feedback of all elements of cost (recurring, non-recurring, direct, and indirect) associated with product manufacture. Develop models to analyze actual vs. predicted cost, including tools to refine model fidelity by reducing uncertainty and variability.

  – **Integrated Process Models & Simulations** – Develop tools and techniques to incorporate material and unit process models and simulation tools into automated process planning tools through transparent interfaces and linkages to enterprise databases. Develop the capability to perform

"what-if" and sensitivity analyses for optimization of multi-step processes and to generate simulation-based models and codes for process control, operation, and verification.

– **Capability & Enterprise Models** – Develop tools and techniques to incorporate process capabilities and enterprise models into the automated process planning tools for optimization of assets and resources and risk mitigation strategies.

- **Goal 2: Interoperable Enterprise Modeling Framework** – Create an interoperable framework for enterprise models that supports manufacturing and business decision-making across the extended enterprise. (S)

  – **Enterprise Model Standards** – Establish standards specifications for enterprise data and industry-driven enterprise models to enable the integration of capacity and resource data from OEM and supplier facilities into enterprise models and virtual product models.

  – **Integration of Process Capability & Enterprise Models** – Develop interfaces, linkages, and databases for integrating material and process capability models with enterprise models.

  – **Integrated Business Metrics** – Incorporate business performance metrics and drivers within the enterprise models to enable the analysis and optimization of performance against competition and market defined goals.

  – **Enterprise Performance Feedback** – Develop data standards, acquisition methods, and analysis models for real-time feedback of product production performance to the master product model and the design process.

- **Goal 3: Manufacturing Process Plan Advisors** – Create knowledge-based advisor systems and data linkages to enable automated generation and optimization of manufacturing process plans. (M)

  – **Advisor/Model Interfaces** – Create interfaces between the process planning advisor model and data/databases of information gathered and analyses from the enterprise manufacturing environment to guide decision-making process for optimizing and perfecting material and manufacturing process plans.

  – **Demand-Responsive Models** – Create demand-responsive planning models. Establish mechanisms for sensing demand information to enable the process plan to react and tailor the manufacturing process to changes in demand triggers and signals throughout the enterprise.

  – **Optimization Algorithms –** Create underlying optimization (setup, business requirements, product mix, etc.) algorithms for all individual unit materials and manufacturing processes and establish the linkages for integration into process planning advisor systems and other enterprise models.

Future State Vision for Production Cost Modeling

The cost of every material and manufacturing process, from elemental material processing through disassembly and recycle, will be thoroughly understood, accurately captured, and electronically linked to bases of estimates and variable factors, enabling continuous and complete visibility into all aspects of product cost.

In the future, all forms of cost – acquisition, nonrecurring design and development, engineering changes, recurring production, product ownership and support, and retirement – will be thoroughly understood and always available as a real-time input for decision making in all phases of product conceptualization, design, manufacture, and support. Costs will be readily predictable for new and emerging materials and manufacturing processes based on models and rules that combine parametric analyses, asset utilization algorithms, ownership algorithms, and probabilistic analyses. Cost throughout a supply stream will be easily modeled based on agreed-to cost elements from qualified and preferred suppliers using verified costing standards common to industry. The virtual model for any product will be capable of generating

cost values in real time for decision-making and optimization to support design iterations and changes, materials and manufacturing process development and improvements, supplier selection, performance evaluations, and other product ownership considerations.

All aspects of cost will be integrated into product and strategic company business decisions such as asset investment, new product or process development, growth, market response, new market entry, or partnering and supplier selection. Accurate life-cycle costs versus performance tradeoff analyses will drive all product and business strategies. The cost implications of any environmental impact of materials selections, which manufacturing processes will be used, the selection of various suppliers, and the disposal and recycle requirements, will be understood and integrated into the product life-cycle analysis. The uncertainties and variations associated with cost will be managed with probabilistic models applied for all elements of cost, enabling high-fidelity decision making, thorough margining for risks, and rapid response to unforeseeable events that impact costs.

Goals & Requirements for Production Cost Modeling

- **Goal 1: Multi-Dimensional, Object-Oriented Cost Models** – Develop multi-dimensional (non-recurring, recurring, ownership) object-oriented validated cost models that incorporate all elements of cost for product and processes and are fully integrated into virtual product models. (M)

  - **Cost Tools Linked With Design Maturity** – Develop validated and certified cost tools that are linked with the different stages of the design process such that the fidelity and detail of the analyses of cost elements are appropriate for the level of maturity of the analysis.

  - **User Query Interfaces for Cost Modeling** – Develop user "wizards" and intelligent interfaces that enable ease of use through queries and templates for applying cost modeling throughout the engineering functions in design and manufacturing.

  - **Product & Process Cost Drivers** – Identify, through value stream mapping methodologies, the major cost drivers for all common product and part families, materials and manufacturing processes, and life-cycle costs. Establish methods to archive, update, and refine the data and make available for any level of analysis needed in product and process development.

  - **Sensitivity Analyses** – Develop models to analyze the sensitivities for all of the various elements and types of costs for multi-dimensional cost modeling for product and process applications. Integrate sensitivity output into decision-making algorithms that relate uncertainty and sensitivity into risk models.

  - **Cost Uncertainty Models** – Develop models and information elicitation methods to develop and quantify uncertainties for any aspect or element of recurring or nonrecurring cost for products or processes based on probabilistic, statistical, and other mathematical relations tools. Incorporate uncertainty models into virtual product models and optimizations.

- **Goal 2: Cost Models Incorporated into Enterprise Models** – Develop linkages and interfaces for product and process cost models and analyses to enterprise level and resource planning tools enabling comprehensive planning and selection decisions for resource, capability, and capacity management. (M)

  - **ERP/CRM Links** – Develop interfaces and linkages from cost modeling tools to enterprise resource planning and customer requirements management tools for performing cost tradeoffs for material, process, supplier, and partner selections and for monitoring and tracking analysis functions for improvement and optimization.

  - **Validated & Certified Cost Models** – Develop the standards, specifications, and templates for cost models based on their emphasis, required maturity for interaction with engineering analyses and integration with virtual product models. Define certification criteria and establish methods to integrate predictive cost models with accounting systems to enable use with enterprise models.

Future State Vision for Process Validation & Certification

High-fidelity process and equipment models coupled to comprehensive materials models and a rich base of scientific knowledge and captured experience will enable all but the most critical processes to be verified in the virtual realm, radically reducing the cost and time of new process qualification and certification.
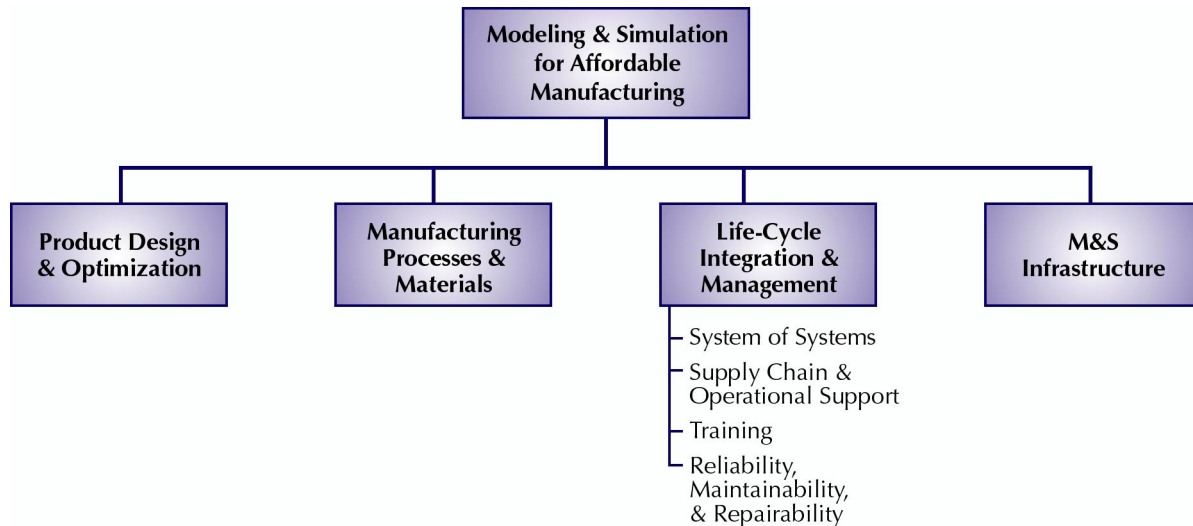
In the future manufacturing enterprise, comprehensive, industry-wide verification and validation standards and methods captured in a mathematically accurate synthetic environment will enable materials and manufacturing process models to be tested and certified for performance and accuracy entirely in the virtual realm. Verification and validation will be based on use within a standard interoperable enterprise and product model, and results and output will be certified within defined boundaries and parameters. Destructive testing and most forms of physical testing will be nearly eliminated from all product and process verifications, except in the most stringent safety-critical applications.

Application of validated model/simulation-based process controls will yield verified product the first time and every time. Critical process control parameters will be defined and modeled to accurately quantify the boundaries, ranges, and sensitivities that impact product quality. Vital material properties and behaviors will be understood and controlled based on modeling and simulation data integrated with real-time, non-intrusive sensing and monitoring of process signatures. This will enable certification of product quality based on verified process quality, all but eliminating the need for final inspection and acceptance.

Goals & Requirements for Process Validation & Certification

- **Goal 1: Verification & Validation Criteria for M&S** – Develop mechanisms and criteria to support verification and validation for materials and manufacturing process models and simulation tools. (L)

  – **Decision & Validation Theory** – Create a forum for demonstration and integration of validation concepts and theory between materials and manufacturing process simulation tool developers and experimenters. Initiate R&D projects for decision theory and validation methods and tests for the control of materials and manufacturing processes based on application of M&S tools for process development.

  – **Verification & Validation Standards & Criteria** – Develop the criteria, standards, and tests for data, model, and simulation tool verification and validation. Establish certification criteria for data and results from the application of M&S tools.

  – **Uncertainty Management** – Identify the role of variation and uncertainty in the application of materials and manufacturing process models and simulations. Develop methods to quantify and "bookkeep" uncertainty across the framework of multi-model and multi-scale analysis tools. Integrate uncertainty into the validation process.

- **Goal 2: Validation Testbed** – Create a center or forum for verification, validation, and certification of models where software developers can evaluate tools in a testbed for accuracy and interoperability, and application across ranges of conditions. (S)

  – **Collaborate with Associations** – Create synergy and interaction with ongoing validation/ verification activities and research within organizations such as AIAA, ASME, DMSO, and other national or academic laboratories.

  – **Certification Standards** – Develop certification standards and criteria for verification and validation to be applied in the testbed to certify models and tools for use in product optimization systems.

  – **Validated Models Repository** – Create a repository for validated models and tools that have been verified through the validation testbed for use in certified manufacturing processes.

5.0 LIFE-CYCLE INTEGRATION & MANAGEMENT

ELEMENT DEFINITIONS	
System of Systems	Includes all aspects of M&S related to evaluating and optimizing the attributes and performance (including cost and within the context of the business case) of a product with respect to all other products with which it will interact in operational usage. Includes issues such as material and component compatibility and inter-changeability, logistics support, physical and other interfaces, and the synergistic effectiveness of all interrelated systems to meet the customer's goals and re-quirements.
Supply Chain & Operational Support	Includes all aspects of M&S related to extended enterprise collaboration, and sup-ply chain integration and management with respect to optimizing requirements (including demand), design, manufacture, test, and delivery of spares, consum-ables, and other support of the end product, including deployment and transport; provision of spares, consumables, and data; maintenance levels and concepts; and overall supportability.
Training	Includes "what and who" aspects of M&S training related to how to use M&S tools, how to design, manufacture, and test product, how to support and repair product in the field (MRO), and how to operate the product.
Reliability, Maintainability, & Repairability	Includes all aspects of M&S related to design and implementation of servicing of the delivered product, including product, component, and material service life; and concepts and designs for operational troubleshooting, problem isolation, repair/replacement, and refurbishment for return to operational status.

5.1 CURRENT STATE ASSESSMENT FOR LIFE-CYCLE INTEGRATION & MANAGEMENT

Modeling and simulation are becoming increasingly valuable in the design and development of products, but application of these technologies to support the other phases of the product life cycle is still in its infancy. Automated tools have transformed the way product support requirements are managed, customers are supported, products are maintained and serviced, and spares are supplied, with organizations such as the Defense Logistics Agency (DLA) and the nation's automotive and aerospace firms leading the development and implementation of new processes, tools, and disciplines. However, modeling in this arena remains largely limited to use of CAD for design, spreadsheets to predict quantities and costs, geographic information system (GIS)-based models to support distribution planning, and custom-built simulations to support troubleshooting of product support problems.

Table 5-1 provides a high-level view of the current state of art and practice relative to M&S for life-cycle integration and management.

System of Systems

"System of systems" is a concept that arose in the past few years in the defense community with the recognition that we can no longer afford to design, operate, and support complex weapon systems as stand-alone products. In the military environment, individual weapons such as aircraft, tanks, and missiles must work together as an integrated system to best accomplish their individual and collective objectives. This concept is even more important from the perspective of the organizations that support all of these products between the factory and the field – maintaining and servicing the product, providing training, troubleshooting problems, and coordinating the competing and often conflicting requirements of different stakeholder organizations.

Application of M&S technologies in this area is in its infancy. Only within the past 2 years have military planners and the contractor community begun to meaningfully address requirements for new and upgraded weapon systems in the context of all of the other systems and assets with which the product must interact over its life cycle. The output of this evolution thus far has been greatly increased emphasis of commonality of parts and subsystems, weapon interfaces, test equipment, and interoperability with deployed and development assets, particularly with regard to electronics. In many cases, the fundamental performance of a new weapon system is becoming a secondary consideration in the procurement equation. Since some 90% of the total cost of ownership (i.e., total life-cycle cost) of a weapon system is attributable to operation and maintenance (O&M), the acquisition community is looking to the O&M community to realize the drastic improvements essential to maintaining warfighting capability in the face of force reductions and limited budgets.

Tremendous amounts of work must be accomplished to turn "system of systems" from a set of principles into tools and applications, and M&S must be a critical enabler of this transformation (Figure 5-1). There is immediate need for modeling and simulation frameworks that support concurrent evaluation, optimization, and management of life-cycle requirements for multiple complex products that will share a common operational environment.

Figure 5-1. Significant advances in M&S technology are essential to enabling weapon system designs to be optimized with respect to all of the other systems with which the product will interact in its operational environment.

Table 5-1. State Map for Life-Cycle Integration & Management

Sub-Element	Lagging Examples	State of Practice	State of Art/ Best Practice
System of Systems	• Ad hoc simulation for design/debug of specific manufacturing activities – not applied in systems context • NASA space solar power station simulations used more for political education • Manufacturing has not embraced with same rigor as "warfighter" community	• Most primes have to some extent – pieces of models & simulations, rarely integrated, or accessible by suppliers or customer; low use in general • Deterministic vs. stochastic • Subsystem, not "system" optimization • Integrated digital environments evolving to support complex, multi-product M&S • High-reliance on models of limited utility (e.g., TAC Brawler) to guide development decisions	• Increasingly sophisticated capabilities and tools at large systems integrators – Lockheed Martin, Raytheon, Boeing, Northrop Grumman for M&S-based operations analysis • USAF, Navy, and USMC making extensive use of M&S to develop 3 variants of Joint Strike Fighter (JSF) with high commonality in design, support, and training
Supply Chain & Operational Support	• Little investment in M&S for depot processes (which are major driver of life-cycle costs and operational availability) • Models not shared among users – everything considered proprietary • MRO organizations not using M&S at depots	• Very limited use of MS below first tier except for design models – low visibility of entire chain • "Forced" integration of M&S across supply chain based on narrow toolset (e.g., Boeing 777) • Sporadic use of simulation to justify equipment & facility upgrade investments	• Automobile industry • Use of internet for enabling (reduces investments) • Getting customer involved (Aero Big 3) • Polaroid projector
Training	• Little or no use of M&S; reliance on books, instructors, and hands on with actual tools or mockups • Generally, very little M&S-based training in industry beyond use of CAD models in training media	• Little use of M&S outside of aerospace community (e.g., flight simulators for military and commercial pilots, sims for space operations training) • Maintenance training still relies on physical mockups and classroom instruction • Increasing use of product models & process simulations ported directly to computer-based training media	• JSF Integrated Training Center model for forecasting of pilot & maintainer training throughput • TACOM (SIMTLC) • VR for Shuttle refurb and training for repair of Hubble space telescope and satellite servicing
Reliability, Maintainability, & Repairability	• Little use of M&S outside aerospace and automotive communities • Older products reverse engineered for life extension • Reliance on simple deterministic models	• Armstrong Labs RAM program • Design for R&M at component and subsystem levels • Standard MTBF, MTTR, etc. models • Reactive vs. proactive • Sporadic use of simulation	• "Ergo man" simulations for development of military aircraft maintenance and repair processes

Standards are needed for integration and interaction of discrete products as multi-element systems without compromising the fidelity of individual elements. Analytical tools are needed to enable designers and planners to study the effects of different approaches and strategies for a given product, and to understand the impacts of different options on other products in the total system context. Security must be provided to enable broad sharing of information across hundreds of supply chain members, with assured protection of proprietary and classified data.

Supply Chain & Operational Support

M&S is becoming increasingly valuable in the supply chain and operational support environment for complex products, but tremendous disparity exists in the level and degree of utilization across different industry sectors and across organizations within each sector. Pockets of excellence do exist. NASA, for example, applies sophisticated simulation capabilities in planning operations for orbital missions such as satellite repair and many aspects of Shuttle and Space Station activities. The large auto manufacturers and aerospace prime contractors use M&S tools in designing and developing operational support concepts and assets, although these tools are little used beyond the design and planning stage except as needed to support troubleshooting. Significant investments are being made in addressing this deficiency in programs such as the DoD's Joint Strike Fighter (JSF), where the prime contractor must interact with hundreds of suppliers and multiple customers (USAF, USN, USMC, and international customers) to support three highly common variants of the next-generation aircraft which will be deployed worldwide in very large numbers.

Below the first tier of prime manufacturers, however, M&S tools are used only in spot applications. Most lower-tier suppliers cannot afford to acquire such sophisticated tools, or to maintain the in-house expertise needed to apply them as a normal course of business, except where mandated by their customers for specific products and projects.

At the depot level where most significant maintenance and repair is performed for the aviation and defense communities, use of M&S tools ranges from limited to nonexistent. Recurring problems and issues in maintenance and repair of specific products are referred back to the original supplier or prime contractor, which imposes long delays between problem identification and problem solution. For many military aircraft that are no longer supported by their original manufacturers (or those manufacturers are no longer in business), depot personnel must physically reengineer parts – incurring costs that must be accommodated within fixed, limited budgets.

A major barrier to expanded use of M&S tools in operational support is the fact that members of a supply chain are universally reluctant to share product information beyond the mandatory requirements of their contract. Breaking this barrier will require sweeping changes in the basis of competition and changes in federal regulations regarding data rights – in effect requiring all members of a supply chain to figuratively make the "source code" for their products available to all other members of the supply chain. Practical steps toward more open product data sharing, beginning with basic CAD models (Figure 5-2) are essential to meaningful advances in this realm.

Lack of infrastructure is another key barrier. The M&S community must develop and provide better,

Engineering Data → **Resulting Media Elements**

Conversion Utilities

- Prime & Subcontractor 3-D CATIA Models, Design Specs, Data Packages, etc.

Concurrent Courseware
- Technical data elements linked to media elements in training courseware, devices, etc.
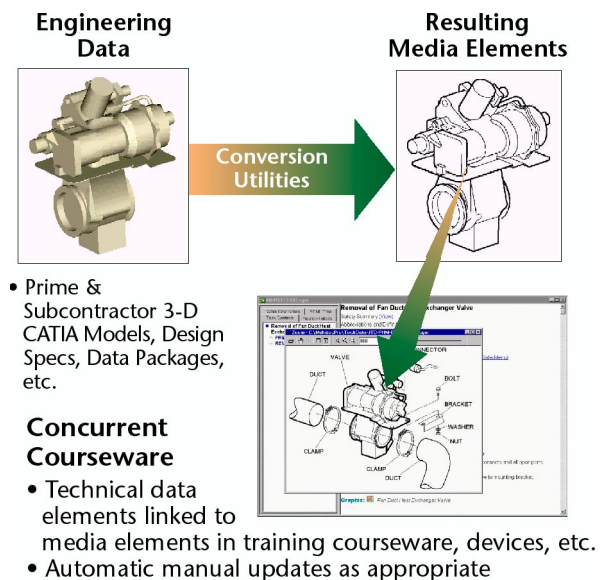- Automatic manual updates as appropriate

Figure 5-2. Sharing of model-based technical data greatly reduces the cost and time of developing O&M documentation, and assures that all supply chain members are working with the exact same data and version information.

easier-to-use tools that all members of the product life cycle can afford, and standards must be developed to define how M&S applications can interact in a distributed environment – with appropriate security – to support the many functions associated with product support from initial delivery to product retirement.

Training

Training is an area where M&S technologies can deliver tremendous value, but benefits have been slow to materialize because training is undervalued in the product equation and the needs of training staff invariably come last in the planning and budgeting process. The aerospace industry has made significant investments in M&S technologies for training of astronauts, aircraft pilots, tank gunners, and other "vehicle operators", largely in the form of costly special-purpose simulators (Figure 5-3). Many simulation programs within DoD have been expensive, high-profile failures, creating a legacy that has been very difficult to overcome.

However, technology advances in desktop computing power are enabling system designers to shift more training to lower-cost platforms. Government initiatives such as the Marine Corps Aviation Simulation Master Plan program are pursuing radical improvements in training cost and quality through use of common M&S technologies and simulators that support multiple aircraft from a common baseline. Virtual reality techniques, driven in large part by advances in the video gaming industry, are enabling pilots to accomplish more training with less reliance on full-scale simulators – thus reducing the need for massive physical simulators mounted on multi-axis motion bases.

3D CAD is enabling significant improvements in the quality of training while reducing the cost of developing and maintaining training materials. Product models generated by designers are now being ported directly into training media, eliminating much of the cost of creating graphics and enabling training designers to work directly in automated environments to produce multimedia training materials. Assembly models and simulations developed to optimize product manufacture are being used directly to support training of maintenance and repair staff. CAD designs can also be downloaded to stereolithography systems to produce physical models, thus reducing costs associated with creating hands-on training aids while providing exact form/fit replicas – which is invaluable for training of maintenance procedures.

Advances in interactive simulation, being led by DoD programs such as the High Level Architecture (HLA) and the Advanced Distributed Interactive Simulation Technology (ADST) project, are laying the foundation for distributed interactive training. These technologies will enable teams of geographically dispersed individuals to train in shared synthetic virtual environments, ultimately combining both simulators and live assets "in the loop". Numerous M&S technology advances are needed to support such ca-

Figure 5-3. Military and commercial simulators leverage leading-edge M&S technologies to drastically reduce the cost and risk of pilot and tank driver training, and are now benefiting from technology advances to reduce cost and increase commonality in simulator hardware and software.

pabilities, ranging from more robust and comprehensive standards for product models (physics as well as geometry), faster and more powerful – but affordable – processing capability, enhanced visualization, and capabilities for integration of synthetic entities.

Reliability, Maintainability, & Repairability

Reliability and maintainability have long been important factors in product design – particularly in the defense community – and modeling and simulation have long been key tools in those disciplines. However, beyond the use of spreadsheet tools for calculating reliability as a function of parts count or as a function of known and predicted reliabilities of each of a system's components, until recently the application of automated M&S tools in the R&M arena has been very limited.

That situation is changing rapidly, however. In the DoD arena, the military services are under tremendous pressure to extend the life of currently fielded weapons and radically reduce O&M costs for new weapon systems now in the development pipeline. The A-10 close air support fighter, for example, was scheduled for retirement in the late 1990s, and is now required to keep flying until 2030. The B-52 bomber fleet, intended to be supplanted by the B-1B and the B-2, is still flying missions today, with maintenance and repair operations (MRO) organizations resorting to cannibalization, reengineering, and high-tech "duct tape" fixes to deal with 1950s-vintage parts for which no source of supply remains.

M&S capabilities at military MRO organizations are virtually non-existent, due largely to a combination of limited budgets, cultural resistance to process change, and a predominant focus on simply getting the work done that comes in the door. Resources to support technology investments are extremely limited, since the services are already stressed to maintain sufficient levels of investment in acquisition and operations.

On the contractor side, investments in M&S technology for design are paying dividends in terms of helping deliver products that are more reliable and easier to maintain. The evolution of 3-D CAD to support assembly modeling and simulation for reduced cost and improved quality in manufacture has made products far easier to service and repair in the field.

However, many barriers remain. Poor, non-centralized recordkeeping means that it is difficult (if not impossible) to develop the rich databases required to understand the maintenance and repair history of a given product, much less make informed predictions. Feedback from the field to the factory is extremely limited beyond basic warranty service information, which is wholly inadequate for enabling true simulations. Prime manufacturers often have only limited visibility of what happens to their products after delivery, and communication between primes, users, and support functions is fragmentary at best unless there is a serious problem. In these cases the prime focuses its M&S assets to analyze the problem, work with the customer to determine root causes and corrective actions, and implement required changes.

There is also very limited visibility into the true costs of maintenance, repair, and support activities. Particularly in the military environment, these services are provided within the constraints of fixed organizational budgets, and little or no cost information is collected at the product level. What information is collected is widely disparate across different organizations, and there is little basis for developing accurate cost models.

5.2 FUTURE STATE VISION, GOALS, & REQUIREMENTS FOR LIFE-CYCLE INTEGRATION & MANAGEMENT

Vision: M&S functionality will be integrated, transparent, and embedded in enterprise processes and systems, enabling accurate understanding and control of life-cycle factors in product design, manufacture, and support throughout the extended enterprise.

In the future, designers, planners, manufacturing staff, and support organizations will use M&S tools to guide all development, operations, and support activities with full consideration of all phases of the product/process/system life cycle, optimizing designs and processes for performance, cost-effectiveness, and efficiency in deployment, operational usage and support, and eventual retirement and disposal. Models and simulations developed to support the initial steps of product design will be carried and enriched throughout the life cycle as an integral part of the product, supporting manufacturing, training, and all life-cycle support activities. These models and simulations will be linked to data sources and knowledge bases that provide a continuous feed of information that is systematically applied to increase their depth, fidelity, and usefulness.

Vision for System of Systems

M&S processes and tools will be transparent to model structure and format, and fully integrated to provide dynamic, comprehensive life-cycle models that address all aspects of multiple interrelated product development and enhancement (technology insertion), manufacture, operation, and maintenance, combined with a real-time simulation capability that enables fully informed decisions at all levels of interaction with the product.

Future modeling and simulation tools will support not only the development of individual products and processes, but enable optimization with respect to all other products with which the subject product will interact in its operational and life-cycle context. The design of a new missile, for example, will not only be optimized for performance in terms of range, speed, reliability, and lethality, but fully take into account its relationships with:

- Its different launch platform(s) (e.g., different types of weapon delivery aircraft) and the unique mission configurations of each type of aircraft (e.g., different weapon mixes, fuel loads, and avionics packages)

- The different command and control systems that will direct and control its use and operation along with all of the other weapons on the platform, with the operational force, and in the theater of operations

- The other systems and forces that will be operating in the same scenario – aircraft, ships, weapons, troops, vehicles, C^3 assets, etc.

- The logistics chains and functions that provide for its transport, handling, storage, maintenance, testing, and repair along with all of the other weapons and systems supported by the logistics chain.

System-of-systems optimization will be of particular value in aircraft carrier and forward airbase operations, where a very large number of diverse systems and operations interact in a limited space for long periods of time with constrained resources.

Military planners and personnel will be able to "fight" in virtual reality (VR) environments where the interactions of different assets are represented with increasingly higher levels of complexity and fidelity, replacing simple loss exchange ratio axioms with accurate representations of real-world results. The effect of introducing a new electronic countermeasures technique, for example, will not be based on a sim-

ple set of rules, but on accurate physics models (e.g., capturing properties such as waveform and attenuation profiles) that interact in the simulation space with the individual electromagnetic properties models of all threat and friendly force assets in the simulation.

Automotive designers, as another example, will use simulation models of the logistics chains for all of their current products to optimize the manufacturability and supportability of a new car design, in areas such as sharing of sources of supply for common and similar parts in both manufacture and dealer support to customers. This will streamline supply chains for after-sale repairs and maintenance, and allow greatly increased commonality of parts, tools, and procedures.

System-level product models and simulations will be shared in controlled repositories (with appropriate levels of security for proprietary and military applications) that enable designers to quickly and transparently link their product to others for system-of-systems evaluation. This will enable design systems to provide designers with automated alerts and warnings when a contemplated design choice would have negative impacts on products already deployed, such as creating a requirement for yet another unique maintenance tool when an existing tool could be used with only an inconsequential change to an aspect of product design.

True system-of-systems M&S capabilities will provide their highest benefit in terms of affordability, cost avoidance, and cost savings, enabling design concepts to be evaluated not only for their own inherent cost, but for their cost in terms of the total context in which they will be used and supported.

Goals & Requirements for System of Systems[17]

- **Goal 1: System-of-Systems Life-Cycle Models** – Develop system-of-systems life-cycle models for different product families and manufacturing sectors (e.g., commercial aircraft, military weapon systems, consumer products) that serve as a primary tool for guiding product design efforts, as a "controller" and single-point source of decision making about the product and its processes. (M-L)

    – **M&S Tools for Systems-Based Life-Cycle Planning** – Develop and pilot M&S capabilities supporting requirements definition, problem-solving, tradeoff analysis, and prediction of decision impacts anywhere in the product life cycle (including future technology insertions) in the context of the environment in which the product will function.

    – **Multi-Product Model & Simulation Interfaces** – Develop standard data interface definitions for individual product types, enabling integration of individual product models into "product family" models that support system-of-systems design understanding. Include the capability for interaction within related product families (e.g., automobile product family models linked to transmission product family models linked to transmission repair tools product family models linked to transmission repair process models).

    – **Interoperable Product Life-Cycle Modeling Databases** – Develop federated databases of all life-cycle information by life-cycle aspect, by product, by industry sector.

    – **Real-Time Model Feeds** – Develop tools and processes for acquisition and provision, to life-cycle modeling systems, of all information relevant to decisions about life-cycle actions and activities, including cumulative life-cycle history information such as repair trends and spares demands.

    – **System-of-Systems Data Mining** – Develop capabilities for mining of information about multiple products with which the product under design will interact in operational usage.

- **Goal 2: Scaleable System-of-Systems Life-Cycle M&S Architecture** – Provide a scaleable architecture for an integrated system-of-systems life-cycle product/system/business simulation environment. (M-L)

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[17] Each of the M&S Goals includes a rough approximation of the time required for its attainment, given as (S), (M), (L) or combination thereof, representing short (3-5 years), medium (5-10 years), and long (10-15+ years) timeframes.

- **Multi-Element Life-Cycle M&S Framework** – Develop a open-architecture M&S framework that supports development of models and simulations for all of the products and processes that must interact in a system-of-systems context, including definition of required inputs, outputs, constituent models, and stakeholders.

- **Hierarchical, Composable, Shareable Models** – Establish interface standards and define standard data relationships that support creation of complex models at successive levels of complexity, connecting a complex system-of-systems model that extends down to constituent product parts.

- **Secure Data Compartmentalization & Management** – Provide capabilities for security compartmentalization and long-term retention/management of data to support system-of-systems modeling that integrates data from multiple sources.

- **Uncertainty Bounding Techniques** – Develop mechanisms, techniques, and protocols for identifying, quantifying, and evaluating uncertainty and risk in complex models and simulations.

- **System-of-Systems Pilot** – Develop and demonstrate a prototype system-of-systems model and associated simulations to serve as a testbed for development and validation of enabling M&S technologies.

- **Goal 3: Scaleable Multi-Product Cost Structures** – Develop scaleable cost data structures, down to lowest product/process levels, that support every phase of the product life cycle, including development, design, manufacture, operation, and life-cycle support, for multiple interrelated products. (M)

  - **Product/Process Cost Data Standards** – Develop and establish conventions for representing and capturing cost information to the lowest level of detail for discrete kinds of products and processes, supporting automatic integration to create system-level cost models that retain linkages back to the models of all system constituents.

  - **Prototype Multi-Product Cost Model** – Drawing on existing cost models, create a prototype integrated life-cycle cost model for one or more high-profile products to develop techniques for integration and to demonstrate the value of such models.

  - **Rate Code Mapping** – Work with major manufacturers and vendors in different sectors to develop mappings of individual company costing structures to a common structure that supports creation and maintenance of systems-level cost models, with appropriate security for protection of sensitive cost information such as rates and factors.

- **Goal 4: Virtual Systems Test Environment** – Develop comprehensive virtual test environments that support testing and evaluation of complex products and systems of systems. (M-L)

  - **Test Environment Requirements Definition** – Define what kinds and extent of physical testing can be replaced by virtual testing for different classes of products and product families.

  - **Integrated Physical/Virtual Testing** – Develop techniques to integrate the results of physical testing into the virtual test environment, for different types of specific tests and including the ability to use and interact with real-time feeds from tests (e.g., using feeds of aero turbulence data from an aircraft flight test to support a parallel virtual test of a captive-carry simulation).

  - **Virtual Testing Tools** – Develop enabling tools (both software and hardware) for virtual testing of products of high interest to different manufacturing sectors, including supporting databases for different product types/classes.

  - **Virtual Testing Validation Strategies** – Develop procedures and strategies for validating the accuracy of virtual testing and bounding relevant uncertainties for different types and classes of products and product families.

- **Goal 5: Life-Cycle Model Connectivity to Operational Data** – Develop protocols and data communications and management techniques supporting the provision of real-world life-cycle data to the enterprise M&S system, enabling system models and system-of-systems models to be continuously updated to enhance their fidelity and value. (S-L)

  – **Data Feed Mechanisms** – Identify and develop means for capturing, verifying, and delivering needed live data for different types and families of products.

  – **Database Interfaces** – Establish formal interfaces with specific manufacturer and customer databases of life-cycle information such as spares and consumables drawdowns, frequency of maintenance and repair actions, field modifications, user feedback on performance and problems, and similar information relative to product designs and costs.

- **Goal 6: System of Systems Culture** – Develop and conduct programs that support the development, extension, and refinement of system-of-systems M&S methodologies, enabling their evolution as a fundamental tool for guiding product development in different industry sectors. (S)

  – **Test Case Partnering** – Identify and engage near- and mid-term targets (companies, organizations, and programs) for prototyping of system-of-systems M&S methodologies.

  – **Test Case Implementation** – Develop business models, supporting metrics, and enabling tools for piloting of system-of-systems M&S methodologies with selected partners, in cooperation with their vendor community; use product pilots to demonstrate value of system-of-systems M&S in different sectors.

Vision for Supply Chain & Operational Support

Changes in the basis of competition will support distributed modeling and simulation across the full span of the extended enterprise, from the customer to the prime manufacturer to the lowest levels of the supply chain. M&S tools will draw on a complete base of shared knowledge and data to provide an intelligent, integrated, multi-tiered view of the product at every phase of the product life cycle.

In the future, all product life-cycle support activities will be guided and managed using a master product life-cycle simulation model linked to "live" product information. Logistics planners, for example, will collaborate directly with customers using the master model to optimize requirements for spares – what will be required, how many, when and where they will be needed, how they will be staged and delivered, and what support assets must accompany them – based on accurate prediction of reliability at the system, subsystem, and part levels. Reliability calculations such as mean time between failure (MTBF) and mean time to repair (MTTR) will be based on robust operational simulations that take into account the probable impacts and effects of operational (e.g., naval, desert, arctic, space) environments.

Designers will use this same information to optimize product designs for maintainability, reliability, and other supportability attributes. M&S tools will enable designers to rapidly explore options for configuring and integrating product elements so that the parts or assemblies most likely to fail, or requiring the most maintenance attention, can be quickly and easily (and safely) accessed by maintenance personnel in the field, using a minimum of special tools. Designers will also interact with the simulation model to determine the life-cycle and supportability impacts of proposed design changes, linking to the supply chain management system to rapidly get cost/schedule/technical impact assessments from affected suppliers and vendors.

The master product simulation model will also provide the basis for all work instructions related to product support. Maintainers, for example, will be able to call up the product model on their desktop or heads-up display, quickly "click down" to the area of interest, and bring up a simulation and instructions for servicing the part, module, or assembly. Analytical M&S tools will enable depot staff to troubleshoot complex problems and use the master product model to quickly evaluate the feasibility of different solu-

tion approaches. Depot staff anywhere in the world will also be able to collaborate in real time with design staff back at the prime manufacturer and supplier sites, using the simulation model to point out problems and rapidly iterate suggestions for corrective actions such as changes to the design or to maintenance/repair procedures.

Depot staff will also use the master model to fix problems on site, without having to go back to original suppliers. This is critical where a supplier is no longer in business, or no longer supports the product. Using the master model, depot staff will be able to call up a part design, modify it if needed, then download the part model (with associated machine instructions) to their in-house fabrication systems for manufacture.

Realizing these capabilities will require a significant change in the present basis of competition. Currently, product information at a practically useful detail level is closely held. Customers receive delivered product and required support information – usually basic documentation including operation and maintenance manuals and, in some cases, engineering drawings to a certain level of detail. Achieving true model-based life-cycle support will require the supplier of a part or higher-level product to make accessible all information related to the product, in digital form, in ways that can be shared across the entire supply chain and maintained with continuous visibility.

Goals & Requirements for Supply Chain & Operational Support

- **Goal 1: Revised Competition Paradigms** – Work with the prime manufacturer and vendor communities to develop strategies for open sharing of critical detailed product information in model-based life-cycle support environments. (S)

  - **Competition Workshops** – Conduct a series of industry-wide workshops dealing with changing the basis of competition, to gain industry concurrence on new competitive models that allow open sharing of detailed information across the supply chain.

  - **New Business Models** – Develop new competitive business models (including contract issues) that support sharing of life-cycle data and information.

  - **New Paradigm Pilots** – Select and conduct a series of small-scale DoD or commercial procurements to pilot and evaluate the revised competitive model of open data sharing, and document the resulting benefits.

- **Goal 2: Shared Modeling Assets** – Provide affordable, easy access to appropriate data and models to all participants throughout the value chain. (M-L)

  - **Shareable Models** – Develop accurate product life-cycle models and simulations that encompass and are shareable across the entire supply chain.

  - **Affordable M&S Tools** – Work with the vendor community to create and deliver affordable, low-cost solutions for product/process modeling by all supply chain members.

  - **Shared Data Management Strategy** – Develop a data management strategy that enables all tiers of the supply chain to input, access, store, share, and protect information and models.

  - **Supply Chain M&S Pilots** – Conduct a series of pilots across different kinds of supply chains (e.g., automotive, aerospace) to evaluate concepts and tools for collaborative M&S of life-cycle functions and activities.

- **Goal 3: Real-Time Access to Maintenance Data** – Provide the capability to use real-time feedback from maintenance activities in predictive maintenance/support models to support planning and management of logistics and maintenance/repair depot operations. (S-L)

- **Model Linkages to MRO Management Systems** – Develop linkages between master product models and maintenance/repair operations (MRO) management systems to support forecasting, prioritization, and conduct of work, resupply/reorder, and similar MRO functions.

- **M&S-Based Maintenance Management Pilots** – Pilot and demonstrate M&S-based control concepts to quantify the benefits of M&S-based control of MRO activities, and migrate the enabling tools and concepts to other supply chains, programs, and products.

- **Goal 4: Supply Chain Life-Cycle Modeling Capability** – Provide supply chain M&S capability including functionality for problem definition, problem-solving, tradeoff analysis, and prediction of decision impacts (including impacts of downstream technology insertion) at different levels of the product value chain. (S-L)

  - **Life-Cycle Modeling Framework** – Evaluate currently available life-cycle models and design a framework for integrating and extending these models, and facilitating their interoperability.

  - **Supply Chain Model Specification** – Develop a scope and capability specification for a master life-cycle simulation model of a selected product and its supply chain interactions.

  - **Supply Chain Life-Cycle Model Pilot** – Develop and demonstrate an integrated life-cycle simulation model for a selected product, that provides functionality for problem definition, problem-solving, tradeoff analysis, and prediction of decision impacts across the product's supply chain.

Vision for Training

M&S-based training will be embedded in all enterprise systems across all elements of the life cycle, enabling users to be self-reliant and empowered to succeed in a continually changing business/ operational environment.

In the future, product and process models created in the product design phase will provide the basis for all training activities across the product life cycle. Product models, for example, will be ported directly into different kinds of training media and manipulated electronically to support specific training needs such as different views of parts and assemblies, and simulations that show how parts fit together and how tools should be applied to perform functions such as testing, servicing, removal, and replacement. The training assets will be linked directly to the master product and process models, enabling training content to be automatically updated (with appropriate alerts) whenever a configuration or a procedure changes.

Robust wireless communications and distributed connectivity will enable users to access M&S-based training on demand regardless of their location, and enable seamless integration of virtual and live training to support distributed team training in synthetic environments. As one example, military pilots in ground-based simulators anywhere in the world will be able to "fly" and "fight" against pilots engaging in live exercises (and vice-versa), with accurate real-time representation of interactions, performance, and results.

M&S will support real-time constructive training, enabling instructors to quickly devise and introduce new problem scenarios to more thoroughly test and advance student abilities. In VR-based maintenance and repair training for example, instructors will be able to insert different faults on demand into the virtual scenario to develop a maintainer's ability to recognize, troubleshoot, isolate, and fix different problems.

Product users and support personnel will be able to log into the enterprise's electronic product support system and call up any desired training on demand simply by clicking on the applicable piece of the model and selecting the desired training module from a menu of options. This will enable personnel in all domains to keep current with requirements for both new and refresher training. Evolution of VR interface technologies will enable users to immerse themselves in simulated operational environments and receive

highly realistic virtual hands-on training on demand, including collaborative training with other users anywhere in the world.

Goals & Requirements for Training

- **Goal 1: M&S-Based Training** – Provide M&S tools that support different kinds of training for different kinds of products and processes, and are adaptive for all levels of user. (S)

  - **Training Requirements Definition** – Define levels and types of user training needs for different classes of products, in cooperation with users and training stakeholders (including universities).

  - **M&S Training Pilots** – Identify opportunities for application of M&S-based training techniques across the continuum of training requirements for selected products, and conduct demonstrations and pilots to demonstrate the effectiveness and value of specific tools and techniques.

- **Goal 2: M&S-Based Embedded Training** – Provide M&S tools incorporating embedded training, integrated into operational systems and processes. (S-M)

  - **M&S-Based Embedded Training Concepts** – Develop M&S-based embedded training concepts and approaches for different classes of products in collaboration with industry/government users, academia, and vendors.

  - **Embedded Training Deployment Plans** – Develop plans for deployment of embedded training technologies and applications for selected products or product types in cooperation with customers and tool providers.

  - **Embedded Training Technology Evaluations** – Pilot and evaluate candidate M&S-based embedded training concepts, technologies, and techniques for selected products.

  - **Effectiveness Evaluation** – Evaluate effectiveness of M&S-based embedded training in initial and ongoing implementations.

- **Goal 3: Training Connectivity** – Develop methods and mechanisms to link training material content to model-based source information and support real-time interaction between live and virtual training activities. (S-M)

  - **Real-Time Linkage to Design Baseline** – Develop methods and protocols to link product data and representations contained in training media directly to the configuration-controlled master product model maintained by the customer and prime contractor.

  - **Automated Change Integration & Alerts** – Develop techniques and procedures for automatically updating training materials when a product configuration change is authorized, and alerting trainers and training users when such change occurs so that users can receive needed updates and trainers can update associated instructional content.

  - **Integration of Virtual, Live, & Constructive Training** – Develop approaches, capabilities, and enabling technologies for integration of virtual, live, and constructive (instructor-in-the-loop) training.

Vision for Reliability, Maintainability, & Repairability

M&S technology will provide clear visibility of all aspects of product maintenance to all members of the product support chain, enabling accurate prediction of requirements, accurate identification and analysis of trends, and efficient performance of all maintenance and repair actions over the life of the product.

Future product support systems will use M&S technology to optimize products in the design phase for all aspects of supportability. Integrated analytical tools will systematically evaluate attributes such as reliability and maintainability at the material, part, subassembly, assembly, subsystem, and system levels as the product design evolves. Automated intelligent design advisors will guide human designers to help arrive at the best combination of product performance and cost-effectiveness from both the acquisition and life-cycle perspectives. Manufacturing personnel will use simulated process equipment and factories to "produce" the virtual designs, interacting with the designers to engineer out potential reliability and maintainability problems, and optimize the product design for disassembly as well as assembly – to ensure the product can be easily maintained and repaired in the field under operational conditions. Maintenance experts will interact with the design team in this process, ensuring the resulting designs take best advantage of real-world experience with similar products.

The design process will extensively leverage designs and experience for similar products already in the field, enabling maximum reuse of existing support assets such as special tooling, fixtures, and test equipment while minimizing requirements for creation (and support) of new assets.

Completed product designs will be "uploaded" to the enterprise knowledge base in the form of a master simulation model, enabling support operations and staff anywhere in the world to accomplish needed planning, training, and provisioning by the time the first product is delivered to its users.

Maintenance staff will use the master product simulation model to execute and manage all life-cycle support activities. As maintenance, repair, and provisioning services are performed, the support system will log all product activity and continuously compare actual to predicted performance. Variances from design spec will be automatically flagged to enable prompt analysis and support warranty actions. Maintenance staff will be able to call up the master product model from anywhere in the world and run analytical tools to ferret out problems and evaluate options for corrective actions. This includes the capability to "ping" the original manufacturer or supplier and bring the design team into the loop to analyze specific failures, problems, or trends, and collaborate interactively in a shared virtual environment to design, test, and validate fixes or work-arounds.

Supported by wearable computers and heads-up displays, maintenance and repair personnel on the line will be able to "boot up" the master product model and navigate to the desired part, module, or assembly, and compare the virtual representation to its real-world counterpart to aid in servicing or troubleshooting. The model will enable them to call up, on demand, any desired information – such as tools required or sequences of events for removal, replacement, and test. With appropriate sensors, the maintainer will be able to use the master model to autonomously monitor execution of the required task in real time to verify that it is being performed correctly.
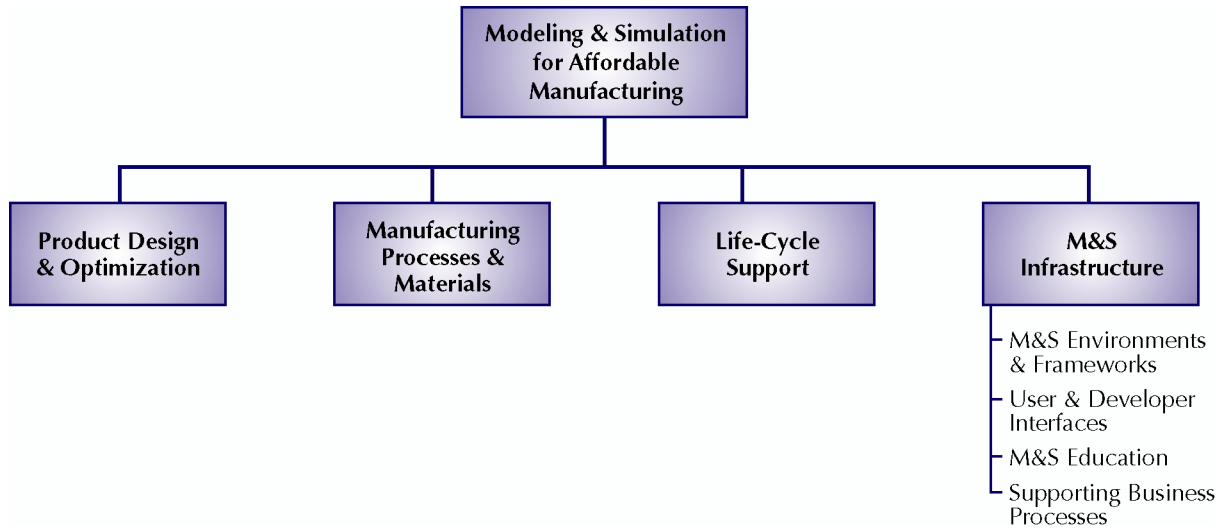
Goals & Requirements for Reliability, Maintainability, & Repairability

- **Goal 1: M&S-Based Maintenance & Support Culture** – Change "depot" business culture to embrace M&S as a standard tool for doing and managing business. (M)

  - **Stakeholder Engagement** – Identify specific stakeholders in the MRO environment and engage in opportunity assessment to define near- and mid-term opportunities for introduction of M&S capabilities to improve operational and business performance.

- **Targeted Opportunities** – For selected stakeholders, develop plans for pilot M&S implementations and develop supporting business cases to justify required investments; develop business models and supporting metrics for different applications.

- **MRO M&S Pilots** – Demonstrate the benefits of M&S cultural change via focused pilot(s).

- **Goal 2: Product Support Feedback to Design & Planning Functions** – Provide the ability to capture information and data from the field and MRO shop floor to feed back into the M&S system to improve the fidelity and depth of product life-cycle models, and to provide real-time management of MRO activities. (S-M)

  - **Product-Specific Infrastructure Modeling** – Identify required information and enabling data structure, including interfaces, environments, and feedback loops to all other life-cycle functions (design, manufacture, etc.) for different types of MRO operations (e.g., aircraft vs. automobiles vs. space systems).

  - **Model-Based Data Management Strategies** – Define mechanisms for model-based data capture, retention, and sharing among all stakeholders.

  - **Real-Time Data Feeds** – Develop methods of integrating real-time streaming data into product support models and simulations.

  - **Data Analysis Capabilities** – Develop applications for cumulative characterization of product support trends over time, trend analysis, and feedback of results to the design function.

  - **Model-Based MRO Pilot** – Develop and pilot model-based MRO management system with connectivity to all supply chain members and functions.

- **Goal 3: M&S Tools for R&M Design Optimization** – Provide M&S capability to determine, in the design phase, the proper parameters and target values for product reliability and maintainability (and other factors); to predict the reliability and maintainability of candidate designs at the material, part, subsystem, and higher levels of assembly testing; and to quantify associated risks. (M)

  - **Integrated Test Concept**: Define what kinds and extent of physical testing can be replaced by virtual testing for different types and families of products, and develop techniques for integration of specific physical testing with virtual testing to provide a complete product testing solution.

  - **Virtual Test Tools** – Develop enabling hardware and software tools for virtual testing for different types and families of products.

  - **Test Support Databases** – Develop supporting databases for virtual testing of different product types/classes.

  - **Virtual Test Validation** – Develop procedures and strategies for validating the accuracy of virtual testing.

- **Goal 4: Virtual MRO** – Provide detailed simulation models of maintenance/repair operations that enable all aspects of MRO activities to be exercised in the virtual realm to support planning and management of operations. (S)

  - **Pilot Selection** – Work with the MRO community to evaluate and select candidate operations for conduct of a virtual MRO pilot.

  - **MRO "Virtualization"** – Work with the selected MRO and the M&S vendor community to build a high-fidelity simulation of MRO processes and assets that support one or more products of interest.

–   **Supporting Product Simulation Models –** Work with the prime manufacturer and suppliers for the selected product(s) to create accurate models of the product and simulations of associated processes.

–   **Virtual MRO Testbed** – Apply the virtual MRO capabilities to support ongoing operations and support development and evaluation of enabling M&S technologies, including virtual-realm collaboration with users and supply chain members.

6.0 M&S INFRASTRUCTURE

ELEMENT DEFINITIONS	
M&S Environments & Frameworks	Includes the common computing and information resources, methods, applications, tools, and codes needed to support any and all modeling and simulation requirements and enable integration and interaction of different applications and tools with necessary fidelity and speed. Includes all standards and protocols required to enable "plug-and-play" interaction of diverse models and M&S tools that create and use them across the geographically distributed extended enterprise (including its supply chains).
User & Developer Interfaces	Includes all visualization and command and control functionality required to enable users and developers to operate and interact with models and their associated M&S applications as an integrated element of any discipline/domain toolset. Includes the ability, for example, to invoke analytical simulation from directly within a CAD application and provision of timely supplementary information or assistance to support the user's activity.
M&S Education	Supports all functional domains (including managers and engineers) with education in the value, applicability, and development and use of M&S and M&S tools.
Supporting Business Processes	Includes all aspects of enterprise management and program management and support that enable and facilitate the integrated application of M&S capabilities across different enterprise functions and across the various phases of the product life cycle.

6.1 CURRENT STATE ASSESSMENT FOR M&S INFRASTRUCTURE

The functions and capabilities discussed in the preceding chapters operate within the context of a technical and business infrastructure. In an ideal environment, this infrastructure state should be invisible and supportive, but in current practice is neither. Table 6-1 summarizes top-level attributes of the current state of M&S infrastructure. Perhaps the single largest present barrier to more pervasive use of M&S is that, for all practical purposes, no true infrastructure exists beyond basic computing tools and vendor-specific environments. Besides the information technology components of the infrastructure (computers, networks, software), a robust framework of standards and protocols is required to integrate M&S functionality across diverse models, applications, domains, and industry sectors. There also needs to be greater awareness of the value and capabilities of M&S in order to stimulate improvements in the cost and capabilities of the technology. Comprehensive standards for capturing and representing knowledge are critical to enabling transparent sharing across organizations and application across the different stages of the product life cycle.

M&S Environments & Frameworks

While modeling and simulation capabilities are a key discriminator of the U.S. manufacturing industry, there are significant shortcomings. Today's automotive industry is said to lose a billion dollars a year because their suppliers are unable to use the models (i.e., CAD files) passed down from the prime manufacturer.[18] This is due in part to the fact that top-level models lack the detail and degrees of fidelity needed for suppliers to do their jobs, and partly because the M&S tools used by different suppliers are incompatible with those of the prime. Many lower-tier suppliers do not use CAD systems at all, but rather work from traditional 2-D hardcopy drawings. The workaround to this problem to date has been for prime manufacturers to dictate that their subcontractors use the same CAD tools as the prime. This is a reasonable solution where a subcontractor only supports one prime, but the reality is that most manufacturing subcontractors support multiple customers, and they cannot afford to acquire, operate, and maintain multiple design environments.

A variety of M&S tools exist for evaluating options and simulating manufacturing products and processes, but using these tools effectively requires extensive training and specialized support capabilities. The current focus of most M&S users is not essentially on creating and using models, but on the mechanics of implementing them in a practical way. Most models capture only a small portion of "reality," and much useful information is lost when the model is applied outside of its native application.

Even with the limited amount of information embedded in current models, the amount of real-time computation and processor demand required for simulations (e.g., for rendering) can easily overtax the computing capacities of all but the most sophisticated organizations. Development of computational grids to provide massive distributed computing capacity on demand offers promise for smaller organizations that lack sufficient need or funding for extensive in-house computing facilities. Distributed simulation does raise issues of security, since in most cases product and process simulations are highly proprietary or, in the cases of many defense applications, classified. While information security is outside the bounds of this document, it should be noted that the subject is receiving significant R&D attention from both government and industry, and thus does not represent an undue concern for the M&S community.

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[18] Smita B. Brunnermeier and Sheila A. Martin, *Interoperability Cost Analysis of the U.S. Automotive Supply Chain*, Planning Report #99-1, Research Triangle Institute, March 1999. www.nist.gov/director/planning/strategicplanning.htm.

Table 6-1. State Map for M&S Infrastructure

Sub-Element	Lagging Examples/Barriers	State of Practice	State of Art/ Best Practice
M&S Environments & Frameworks	• Point solutions and proprietary systems • M&S setups and preprocessing are a craft – manual, labor-intensive efforts of multiple groups • Focus is not essentially on the model, but on implementation of model in some tool; need standard model definitions, responsive to evolving needs of industry • Vendors control market via data representation; need open architecture information representation that can be provided by multiple compliant vendors • Current systems capture lower-level data rather than higher-level intent (semantic gap) • Need open systems, but vendor incentive is low due to danger of becoming a commodity • Leading modeling systems do not support diversity of needed models (e.g., STEP Release 1 focus on mechanical CAD models) • Need <u>metrics</u> that measure products created (better, cheaper, faster) as well as the manufacturing processes that create them • Major interoperability problem with legacy systems and knowledge repositories • Lack of a comprehensive theoretical basis for interoperability and product modeling	• Point-to-point integration of monolithic solutions • Single vendor solutions; e.g., PTC ProEngineer, Dassault CATIA • Mathematical packages; e.g., MatLab, MathCAD, FEM • Limited collaborative ability • CAD for geometric modeling • Hundreds of point solutions • In chemical and electrical power industries (no geometry), adaptive grid generation is used, and modular components • Multi-physics, optimization engines; e.g., Engenious • GM, GE working on optimization engines and multi-physics • DOD HLA (high-level architecture) • MAK, PITCH • Intelligent Mfg Systems MISSION to produce commercially viable simulation framework (based on HLA) • CORBA, XML for data exchange • Point utilities, e.g. COM, Java Beans	• Advanced Simulation Center, Lockheed Missiles, Sunnyvale allows development of new models and integration of tools & models, including legacy systems & tools • Advanced, integrated product development environments; e.g., Advanced Technology Labs of Lockheed developed smart product models for Navy's DD21 program; CEE (Collaborative Engineering Environment at Wright-Patterson) • NIST ATP FIPER (Federated Intelligent Product Environment) project • Standards-based distributed simulation capability – testbed at NIST MEO (XML, etc.) • Common Data Model abstraction; work at Sandia • Multi-Representation Architecture (MRA) for design/analysis integration at Georgia Tech • STEP Release 2 with rich information standards
User & Developer Interfaces	• User interface barrier; too many tools too complex for designer to use effectively • Need better way to capture and apply knowledge of experts; can't expect everyone to have CFD (computational fluid dynamics) expertise • Semantics; user's language (holes, slots) not accepted/used by the CAD tools – translated to other tool-specific concepts	• Boeing Rocketdyne's Robust Design Computation System • Point utilities; e.g., COM, Java Beans • Use of IDEF models	• Composable simulations programs; e.g., Carnegie Mellon (CMU) (cf Chris Paredis), CRL, Virginia Modeling & Simulation Center (VMSC), NRL • Lockheed Martin used Technosoft's Advanced Modeling Language (AML) to create integrated modeling environment • Rational suite of tools including Rose (for UML)

Sub-Element	Lagging Examples/Barriers	State of Practice	State of Art/ Best Practice
M&S Education	• Little awareness or understanding of M&S beyond specialized engineering level • Information modeling education typically in Library & Info Science programs • Engineering education focusing mainly on traditional mathematics as a key physical behavior modeling language; engineers need similar education in information and knowledge modeling	• Staff educated in engineering, math, etc. but generally not in M&S • Training is tools-oriented • Limited generic M&S • Enterprise Intranets are used for knowledge capture, training source of M&S practices, design criteria (e.g., Honeywell, Lockheed)	• Graduate programs in M&S, computational science & engineering, e.g., Old Dominion, U of Central Florida • Certification in M&S – definition being developed by NDIA • Electronic, chemical, biological engineering fields much more mature in use of M&S • Leaders for Manufacturing program at MIT stresses importance of M&S • Miss. State U's program in Computational Engineering stresses M&S • Georgia Tech iTIMES Center (decision-based design, engineering information, & knowledge systems)
Supporting Business Processes	• M&S not valued by most companies; management does not understand M&S or know when to use it • Network infrastructure industry (e.g., Cisco) needs to develop models but not doing so • Business case not yet made for M&S infrastructure to justify needed investment • M&S is labor-intensive, both in creating and maintaining models • Core problems are not with M&S technology, but with the extreme diversity and incoherence of business processes across industry and across different sectors	• Six Sigma process modeling used at many leading companies – GE, Honeywell, Bechtel, Lockheed Martin, GM • Design for Six-Sigma uses M&S to predict variation in products & processes before execution – big impact on engineers and management • DoD has SBA initiatives; Army has SMART; AF has Synthetic Battlefields	• SEI Level 5 organizations if it includes M&S, systems engineering • Lockheed Martin "JSF enterprise" • GE, Caterpillar model much of their business operations • Systems Engineering: Design Hub of JPL • Nanotechnology, MEMS, and biotech industries cannot exist without extensive use of M&S

A more fundamental driver for standards is the ability to represent information in ways that support sharing of knowledge through "open" repositories, and enabling independence in use of models and simulations with multiple vendors' systems. Interoperability – the ability of dissimilar models and systems to operate together without loss or corruption of information – is a critical issue. Today's M&S tools are proprietary systems that are difficult to integrate with other tools and which do not support broader application across manufacturing processes or organizations, or across the product life cycle. With proprietary systems, user organizations are captive to vendors' tools. The investments required to learn a tool and to capture the enterprise's information in the format of the tool are a massive barrier to change. This creates a situation where user organizations are captive to vendor pricing and technology – which is certainly good business for the tool vendor, and a powerful disincentive to support efforts at standardization.

Standards are needed to achieve interoperability, but the typical formal standards process today is slow and cumbersome; information technology advances so quickly that in practice, market dominance of leading tool vendors drives the instantiation of ad-hoc standards, sometimes to the detriment of users who have little choice but to invest in "required" upgrades.

There is also a pressing need for effective ways to capture requirements in ways that support model-based design and manufacture. Better metrics are needed, to measure the products created and the processes that create the products. Manufacturers must be able to query and edit models and simulations quickly and easily in order to troubleshoot problems and shorten the timeline from model inception to product delivery.

Finally, techniques are needed that address fundamental issues such as information coverage and semantic gaps, as well as the lack of fine-grained, multi-directional associativity among diverse, multi-fidelity models.[19] Borrowing concepts from electrical circuits, one can imagine primitive information connection elements and knowledge capture building blocks. As the transistor has done for electronics, these elements may provide the basic technology that will fill these gaps and enable true interoperability.

User & Developer Interfaces

The interfaces of current modeling tools are a significant barrier to effective use of M&S. The user's natural language and terminology is often not accepted by the tools, so specific training is required to communicate with the tools in a way that each tool can understand. M&S applications are complex systems that require significant training and experience to use effectively, which quickly leads to bottlenecks when design or analysis demand exceeds capacity. Complex M&S-based analyses frequently require a thorough understanding of underlying technologies such as fluid dynamics or structural crystallography, which drastically raises the bar for user training. There is thus a driving need for user and developer interfaces that are easy to use, that support interaction in a user's natural language and domain terminology, and which allow "one-click" launching of specialized analytical functions while returning results in easy-to-understand terms.

The state of practice for capturing, representing, and applying knowledge in M&S applications also leaves much to be desired. Standard means of capturing knowledge about models and requirements are needed, using neutral knowledge representation mechanisms (such as XML, STEP, UML, CORBA, and SOAP[20]) that support use in multiple environments.

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[19] Russell Peak et al, *Creating Gap-Filling Applications Using STEP Express, XML, and SVG-based Smart Figures - An Avionics Example*, Georgia Institute of Technology, April 2002. http://eislab.gatech.edu/pubs/conferences/2002-apde-peak-gap-filling-apps/.

[20] While XML is a significant emerging technology, it alone is insufficient to address M&S infrastructure needs. XML provides a useful data *format* mechanism, but for effective information sharing the *content* represented in an XML format must still be agreed upon. Combining XML with comprehensive *content* standards such as STEP may enable significant progress. Interface protocols such as CORBA and SOAP are also needed to permit dynamic interactive communication *vs.* today's data exchanges, which are typically batch-oriented and file-based.

Education

Education and training for M&S is greatly lacking across all industries. This is partly because the discipline is an emerging one, where practitioners get most of their core training through academic coursework at universities and self-directed learning in their job environments.

Supporting Business Processes

Current business processes across the breadth of industry do not support use of modeling and simulation beyond limited applications such as 2-D and 3-D CAD for drawings and shape models, and spreadsheets for cost modeling. M&S is labor-intensive and expensive, which is an intractable barrier to wider use. A key factor in making M&S an integral tool in all enterprise processes is finding ways to make it less costly to apply, which will help broaden the user base beyond the current "high priesthood" of practitioners. This will also support sharing and reuse of models and simulations across the different phases of the acquisition life cycle and throughout industry's supply chains. However, industry has so far not made the business case for M&S infrastructure to justify the needed investment. This infrastructure must be put into place to make M&S affordable and pervasive.

The modeling community is too fragmented at present to drive the major changes required to make M&S an intrinsic part of business processes. To promote wider use of M&S and help force consolidation of standards, some have suggested that the government should specifically require use of models and simulations in the performance of federal contracts.

M&S can be a key tool in the discipline of "systems engineering," which is gaining increased importance because of the need to better understand and manage life-cycle costs. Initial results from requirements capture efforts such as AP233 for systems engineering[21] are promising. Such efforts need to be supported further, including increased end user organization involvement. In any case, organizations need a means of getting knowledge, data, and relationships captured in an abstraction mechanism that enables accurate, informed business decisions. Six Sigma process teams in particular require understanding and documentation of all variables in order to optimize processes for quality and efficiency.

6.2 FUTURE STATE VISION, GOALS, & REQUIREMENTS FOR M&S INFRASTRUCTURE

Vision: Enterprise infrastructure in all industry sectors will support all aspects of modeling and simulation to reduce time and cost and improve performance, quality, and responsiveness in product/process design, manufacturing, and life-cycle support. Industry-wide collaboration will enable grater leveraging of M&S investments and widespread sharing of results to benefit all companies in all sectors of the U.S. manufacturing base.

The functions and capabilities envisioned in the preceding chapters depend on a robust and highly capable infrastructure that smoothly and efficiently enables productivity and creativity without concern for where the tools or supporting business functions are, or how to use them. M&S configurations and toolkits will support problem solving planning & strategy with appropriate configuration and information gathering from disparate sources.

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[21] Lead organizations in AP233 development include NASA, BAE Systems, PDES Inc., Lockheed Martin, and INCOSE. Links to overviews are available at http://eislab.gatech.edu/efwig/ and http://www.estec.esa.int/conferences/aerospace-pde-2002/.

Vision for M&S Environments & Frameworks

The M&S environment will enable collaborating stakeholders – designers, managers, customers, and suppliers – to focus on the tasks at hand and not on the mechanics of how to use the tools. The stakeholders will apply and interact with a family of diverse models and simulations (in multiple disciplines and levels of resolution) that bring to bear all information needed to rapidly and cost-effectively support decision processes over the life of the product.

The future collaborative M&S environment will support all enterprise processes and disciplines across the product life cycle, from concept inception to retirement and recycle. The environment will support modeling and simulation of products, processes, and systems at multiple levels of abstraction, capturing and accurately representing relevant entities, their attributes, their behaviors, and their relationships. An industry-standard M&S Concept of Operations (ConOps) and standardized application interfaces will enable intuitive use of the environment and its tools with minimal training.

Drawing from a comprehensive collection of tools – modeling, statistical analysis packages, display devices, high-performance computation servers, etc. – future M&S environments will automatically self-assemble, on demand, to support the requirements specified for a project. The environment will integrate models, simulations, and tools from multiple sources, without compromising the functionality of any of these assets. The environment will be able to receive information from any source media, and will be able to output information in any desired form, while providing adequate but transparent security. Immersive environments and augmented reality will be routinely available when needed. Remoteness of users will not cause reduction of environment functionality.

Future M&S environments will achieve the long-held goal of timely (near-instant) access to the right information when it is needed, wherever it is needed, and however it needs to be presented. The information will be understandable, secure, of known quality (validated, certified, high-quality data if needed), and synthesized to the appropriate level of abstraction for the specific design task, manufacturing task, or business decision at hand.

With such environments, users will be able to easily develop and instantiate simulation models to predict the functions of the product (performance, weight, cost, affordability, producibility, recyclability, etc.) and the processes for its manufacture and life-cycle support.

The framework for these environments will provide seamless, reliable, robust interoperability of distributed models created by different organizations, regardless of underlying tools, systems, time, or location of creation, yielding dramatic increases in accessibility and usability and dramatic decreases in operating cost for new and legacy proprietary and COTS systems and models.

The frameworks of the future will use widely accepted standards for data representation, and for reuse and sharing of models and simulations. Models developed for one purpose will be reused for other purposes, with complete platform and tool independence and with no data reentry required. Different views of models will enable continuity over different phases of the product/process life cycle. Even legacy models, data, and tools will be able to be incorporated into the frameworks.

Users will define and control the overall model (metamodel) of the models, and will control the formation and use of specific models – for example, defining a part family by defining all the artifacts involved from concept through life cycle. Multidirectional associativity will keep the relations coordinated between different parameters.

Future modeling tools will enable the capture of all the input information, representation and storage in customer-controlled open repositories, and output of all the information stored into different functions or presentations with no loss of needed information. This will support synchronous and asynchronous collaboration between groups performing different functions or working on different stages of the life cycle.

Goals & Requirements for Modeling & Simulation Environments[22]

- **Goal 1: Standardized Model Management** – Establish a uniform, adaptable process and standards for management of conceptual and detailed models. (S-M)

  – **Common Model Development Process** – Establish a standard methodology and processes for developing and using conceptual models.

  – **Mandated Modeling** – Integrate requirements for creation and use of standards-compliant conceptual models in government procurements to improve the visibility and credibility of the technology.

- **Goal 2: Flexible Model Structure** – Provide a common modeling structure that supports repartitioning across disciplines, providing different views and configurations as needed and supporting different systems interfaces. (S-M)

  – **Models from Ontology** – For each discipline, develop a standard ontology (including product data structure) that can spawn appropriate data models.

  – **Representation Mapping** – Develop methods and mechanisms to map between representations without compromising desired features.

  – **Multi-level Abstraction** – Develop methods and mechanisms to support multiple levels of model abstraction.

- **Goal 3: User-Defined Knowledge Repository** – Provide a shared knowledge repository of user-defined (not vendor-defined) definitions of class structures, attributes, and information formats, with common approaches for information management and use. (S-M)

  – **Evolving Information** – Provide the ability to deliver information to models as needs, applications, and technologies change.

  – **Multiple Model Integration** – Provide the environment with the ability to incorporate/integrate multiple models from different sources.

- **Goal 4: Efficient Model Use** – Dramatically reduce the amount of time and labor and expertise required to develop and use models and simulations to reach feasible, optimized product and process solutions. (S-M)

  – **Faster Design Iterations** – Develop and deploy engineering systems able to reduce design iteration cycle time (including design/model generation/compute time) by a factor of 10 or 100.

  – **Appropriate Abstraction** – Develop methods to automatically reduce model complexity to the level of abstraction needed for the task at hand, based on a user's requested function.

  – **Self-Assembling M&S Environments** – Provide the ability to automatically assemble an M&S environment to specified requirements, on demand, to support specific project or product needs.

  – **Flexible Input & Output Content** – Provide the ability for models and simulations to receive and output information from/in any media (e.g., input by voice command, numerical data, data link, or merged external model; output to visual display or numerical control code).

  – **Immunity to Technology Change** – Provide a standard M&S environment that adapts responsively to technology changes, without loss of functionality or compromise of data integrity.

  – **Intelligent Assistance** – Provide means of presenting information to engineers as they are making decisions, including alerts and warnings when constraints are violated or when standard parts should be employed.

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[22] Each of the M&S Goals includes a rough approximation of the time required for its attainment, given as (S), (M), (L) or combination thereof, representing short (3-5 years), medium (5-10 years), and long (10-15+ years) timeframes.

– **Model Data Reuse** – Provide mechanisms for reuse and sharing of a model's information and components.

– **Composability Capability** – Develop the ability to automatically combine smaller models and reuse existing model information to create new models.

- **Goal 5: Model-Based Collaboration & Information Sharing** – Provide M&S environments that enable effective collaborative operations and sharing of all appropriate information across the product life cycle and throughout the product supply chain. (S-L)

  – **Change Management Function** – Develop change management functionality that gathers, integrates, interprets, presents, and disseminates, to all affected parties, all pertinent information relative to pending and approved design changes.

  – **Just-In-Time Model Information Feeds** – Provide interfaces and mechanisms that provide the enterprise M&S environment with instant/timely access to accurate, validated information.

  – **Product Prediction Capability** – Provide functionality enabling simulation models to accurately predict the performance, weight, cost, affordability, producibility, recyclability, etc. of products and processes.

  – **Secure M&S Environment** – Provide automated means of protecting and sharing appropriate information from different sources in the distributed enterprise M&S environment.

- **Goal 6: Interoperable Models** – Develop solutions for providing interoperability of new, legacy, and proprietary modeling/simulation systems and their models. (S-L)

  – **Standard Data/Knowledge Representation** – Develop standard, compatible approaches for capture, use, and configuration management of model-based data and knowledge to eliminate errors and significantly reduce associated costs.

  – **Standard Data Definitions & Communication Strategies** – Establish industry-accepted data definitions and communication strategies for model inputs and outputs to/from external data sources.

  – **Multiple Levels of Abstraction** – Define and develop standard model type templates supporting different levels of abstraction, with dictionaries or taxonomies of their content.

  – **Associativity Between Models** – Enable fine-grained associativity that occurs automatically between different models.

  – **Flexible Input & Output Directionality** – Enable use of individual models and networks of models in a multi-directional fashion (i.e., enable changing of which variables are inputs (givens) vs. which variables are desired as outputs).

  – **Interoperability Test Methods** – Develop test techniques to validate methods of interoperability.

- **Goal 7: Communication Mechanisms** – Develop a communication framework for sharing of data, information, and functionality among M&S tools, supporting databases, and users. (S)

  – **Tool Interoperability** – Incentivize M&S tool vendors to make their tools interoperable.

  – **Open, Shared Repository** – Provide an extensible, open repository of knowledge with intelligent adapters for synchronous and asynchronous communication among distributed multidisciplinary models.

  – **Vendor Neutral Input/Output Mechanisms** – Provide means for users to manage and control inputs and outputs, and control models, independent of vendors.

Vision for User & Developer Interfaces

Designers, engineers, managers, and business and support staff will interact with the enterprise M&S environment in an intuitive fashion, using plain-language commands and physical touch-screen controls to create, modify, and use models and simulations.

Future M&S users will benefit from a common interface environment that supports disparate models and simulations built for different purposes with different tools. Problems and commands will be stated conceptually and in plain language, not in machine instructions. Extending the familiar graphical user interfaces of today's computers, future users will be able to use multiple GUI tools (voice, keyboard, mouse, stylus, dataglove) for any M&S application. These interfaces will support all levels of user expertise and enable seamless collaboration among disparate geographically dispersed users, simultaneously accommodating the specific needs of each user.

The interface to the models and simulations stored in, or accessible by, the enterprise M&S environment will be able to provide conceptual maps of the subject area and operating environment, providing alternative views on command, with real-time response to enable intuitive use of the system.

Interfaces to future M&S systems will adapt in real time to the available input or display medium (or platform). For example, the interface may provide an immersive VR simulation experience with full sensory information, or a simple voice or graphic interface for troubleshooting or checking out an idea from a remote location via a dial-up connection.

Future M&S systems will have the intelligence to understand different users' conceptual models and behave accordingly. This will yield anticipatory behavior by the system, and provide the ability to "do what I meant" instead of "do what I said." These systems will tell or show the user only what he/she asks for, and "know" each user by means of a captured profile that is enhanced over time as the user interacts with the system. Supplementary information and deeper levels of detail will be provided on command – or automatically if a user violates constraints such as design tolerances, material specifications, performance regimes, or safety regulations.

Goals & Requirements for Integrated User & Developer Interfaces

- **Goal 1: Natural, Dynamically Reconfigurable Interfaces** – Provide user interfaces to the M&S environment that are dynamically reconfigurable according to the context of use and which accommodate the type of device being used (PC, PDA, etc.). (M-L)

  – **User Customizable Interface** – Develop customizable interface styles (GUI, natural language voice or keyboard) that enable users to quickly configure and reconfigure the modes, methods, and styles of interface to the M&S environment.

  – **Modular Interface Components** – Develop selectable, modular interface components to support customizable interfaces.

  – **VR Interfaces** – Develop M&S environment interfaces that support immersion of users in a 3-D virtual reality context, with command and control via datagloves and voice.

  – **Natural Language Interface** – Develop the capability for the M&S environment to accept and respond correctly to instructions and commands in natural language.

  – **Support for Disparate, Distant Users** – Provide the capability for multiple users to interact/collaborate in the M&S environment using different interface modes and languages.

- **Goal 2: Multi-Model Integration Interface** – Provide a generic GUI/cockpit/dashboard supporting development, integration, and use of multiple heterogeneous distributed models of different types having multiple and varying levels of complexity. (M)

– **Automatic Conceptual Map** – Develop standards and techniques for providing a conceptual map (analogous to a Web site map) of subject areas and model/simulation assets, within the enterprise M&S environment, and automatically updating the conceptual map whenever assets are added, deleted, or modified.

– **User Elicitation Capability** – Provide feedback mechanisms and on-line help functions that process user requests and interactions to solicit/elicit required and optional inputs, outputs, resources, constraints, and actions.

– **Anticipatory Behavior Capability** – Provide system intelligence to monitor user actions and system status and anticipate the next actions to be performed.

– **Automated Command-Driven Model Integration** – Develop an intelligent processing capability that enables two or more models or simulations to autonomously and accurately integrate at a user's command (e.g., automatic self-assembly of a complex product model from discrete models of its component subsystems, or an aero simulation of a wing structure controller automatically integrating into the aero simulation of the fuselage with which it will be mated).

Vision for M&S Education

M&S will be an integral element of engineering and manufacturing-related education and training curricula in the corporate environment as well as the academic environment, supporting both advancement and application of M&S technologies.

In the near future, M&S technology will be an integral subject of education and training for all technical and business professionals in manufacturing and related industrial sectors. Current leading-edge programs at the graduate and undergraduate level will be replicated and emulated across the academic community, providing broad awareness of the capabilities and value of M&S as well as formal education, training, and certification in utilization and applications. Individual sectors and companies will collaborate to develop and deliver specific M&S training to their workforce, and M&S technology developers and vendors will provide a continuous stream of educational and training materials to keep their customer communities current of the latest advances and capabilities.

Goals & Requirements for M&S Education

• **Goal 1: M&S Education Outreach** – Establish an efficient means to educate and train all stakeholders on the fundamental concepts, capabilities, and limitations of M&S, so they are able to critically and effectively apply M&S to solve problems and contribute to the growth of corporate M&S knowledge and capability. (S-L)

– **Corporate M&S Education Programs** – Develop focused curricula (both initial and refresher/update) that can be used in corporate environments to educate executives, functional/project managers, and staff in the capabilities, limitations, and benefits of M&S. Facilitate culture change in stakeholders (from design engineer to CEO) to get the maximum leverage of M&S.

– **Academic M&S Education Programs** – Establish M&S degree programs at graduate and undergraduate levels, modeled after current successful programs and replicated across the engineering and business education community, which provide formal instruction in all aspects of M&S technologies and their applications.

– **M&S Vendor Outreach** – Encourage M&S technology developers/vendors to sponsor formal education and training programs and modules that can be delivered to support both corporate and academic training programs with content that is continuously updated to keep pace with the leading edge of the art.

- **Goal 2: M&S Skills Training** – Provide workers with appropriate knowledge, skills, and training to use M&S tools and interpret, arbitrate, and apply results. (S-M)

  - **Skills Requirements Definition** – Define appropriate knowledge, skills, and abilities required for different user types (level and discipline).

  - **Training Delivery Strategy & Approaches** – Develop training delivery concepts and mechanisms in cooperation with universities, vendors, and end users (including both technical and business perspectives); develop supporting deployment plan in cooperation with stakeholders.

  - **Training Pilots** – Pilot and evaluate candidate M&S training curricula and techniques in initial and ongoing implementations.

Vision for Supporting Business Processes

Future business processes will integrate and dictate use of M&S to support all business decisions, and these processes will support the widespread application and continuing evolution of M&S technology.

In the future, M&S will support all enterprise business processes, and the enterprise's business processes will support application and expansion of M&S capabilities. M&S will be used to guide strategic planning, manage product and process development and implementation, support all facets of physical operations (factory management, product support, logistics, etc.), and support planning and execution of technology refreshment and other long-term enterprise investments.

Investments in M&S infrastructure will be seen as a high-ROI multiplier of capability, not a grudging necessity. These investments will be motivated by the use of metrics that prove the value of M&S in terms of reduced cost, higher quality, and enhanced performance of enterprise products and processes. Incremental implementations with measurable gains will provide growing impetus for needed M&S infrastructure development.

Goals & Requirements for Supporting Business Processes

- **Goal 1: M&S Business Case** – Demonstrate and document the value of M&S-based analysis and decision support applications to prove the impact of M&S as a fundamental enabler of business success. (S)

  - **Common Business Case Approach for M&S** – Develop a formal business case methodology for corporate/organizational implementation and support of M&S infrastructure and applications.

  - **Phase Analysis & Justification** – Develop business cases for M&S investments that support various enterprise processes and phases of the product life cycle.

  - **M&S Value Analysis** – Develop value analysis techniques and tools enabling organizations to make accurate, informed decisions about prospective M&S investments and provide the internal justification to make those investments based on both short- and long-term ROI.

  - **M&S Success Models** – Gather and publish detailed case studies, with verifiable metrics, of successful M&S applications in industry.

  - **Shared M&S Repository** – Establish an openly accessible repository of validated, useful common models, nonproprietary data, and low-cost "shareware" applications that enable multiple companies to easily implement basic M&S capabilities that provide demonstrable benefits.

  - **Mandated M&S** – Develop requirements for specifying use of M&S in the performance of federal contracts, beginning with requirements that track to current industry best practices and become increasingly rigorous over time as M&S standards evolve.

- **Goal 2: M&S Best Practice Program** – Establish a formal program to monitor, develop, and evolve best practices for M&S. (M-L)

– **M&S Best Practice Processes** – Establish criteria to develop, document, and disseminate M&S best practices.

– **M&S CMM Program** – Establish a formal maturity assessment process, modeled after current Capability Maturity Model (CMM) programs for software development, to establish criteria for companies to achieve certified levels of M&S capability.

- **Goal 3: Pervasive Use of M&S in Organizational Decision Making** – Develop tools and techniques to make M&S pervasive across organizations, including establishing ROI requirements, maximizing revenue opportunities, and managing risk. (S)

  – **Models to Reveal Underlying Commonality** – Provide M&S tools to minimize inappropriate variation, versions, options, and complexity of products and processes.

  – **Linkage of Business & Production** – Develop formal, effective techniques to establish linkages between business models and product/process models.

  – **Integration of Risk Management with M&S** – Develop M&S-based risk management (i.e., identification, assessment, and mitigation) tools able to operate based on input from product and process models.

  – **Integration of Marketing & Manufacturing** – Develop methods to integrate and "harmonize" marketing, design, and manufacturing models.

- **Goal 4: M&S-Based Supply Chain Integration** – Provide M&S applications and tools that support harmonious and seamless flow of information and actions up/downstream across the supply chain. (S-L)

  – **Supply Chain M&S Protocols** – Establish standards and protocols for transfer and sharing of models and related data among supply chain members.

  – **Forecasting/Scheduling Supply Chain Operations** – Develop and demonstrate M&S tools to forecast and schedule operations in real time, transparently across the supply chain.

  – **Change Notification Across Supply Chain** – Couple M&S tools with change release systems to provide instant notification and "cascading" of changes across the supply chain.

  – **M&S Information Security** – Develop techniques and protocols for providing multiple levels of security for models and simulations that are shared across supply chains, enabling lower-tier suppliers to work with an accurate product or process model but bar access to the supporting competition-sensitive data on which the model is based.

Appendix A

Modeling & Simulation for Affordable Manufacturing
Technology Roadmapping Workshop

Top 37 Goals[23]

1. Develop techniques to support the automated generation of models at various levels of abstraction.

2. Complete awareness of cost factors, supporting decision making early and throughout the design and manufacturing life cycle.

3. Develop and deliver a scaleable, comprehensive product life-cycle model with enabling architecture and data structures tailorable to all sectors and integratable across all levels of the supply chain.

4. Establish seamless integration of modeling systems to enable multi-discipline optimization delivering impact early in the design process.

5. Establish rigorous mathematical models to analyze uncertainty, and provide validation and certification in M&S including the quantification of uncertainty in models.

6. Develop object-driven data schema from which models are generated, assuring interoperability and reuse (includes common feature sets).

7. Create a tool to produce a process plan for manufacturing operations.

8. Develop a solution to solve the interoperability problem of new, legacy, and proprietary systems and models.

9. Develop systems that maximize the effectiveness of testing through use of performance models realizing "surprise-free" product performance.

10. Develop an interoperable framework for the integration of materials, material processing, and manufacturing models.

11. Develop interoperable models for the integration of materials, material processing, and manufacturing simulations.

12. Create a tool to evaluate process capability to determine producibility of features, resource capabilities, and process repeatability.

13. Establish extensible process and guidance for flexible, ongoing conceptual model management.

14. Establish an efficient means to educate and train all stakeholders on the fundamental concepts, capabilities, and limitations of M&S, so they are able to critically and effectively apply M&S infrastructure to solve problems and contribute to the growth of corporate M&S knowledge and capability.

15. Develop a heterogeneous open architecture environment that provides defined interfaces between elements (from cradle to grave). The environment merges elements of operational analysis, mechanical systems, variability, electrical, manufacturing, etc.

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[23] As determined in the M&S workshop prioritization process.

16. Quantify sensitivity to variations and define limits in design and manufacturing robustness leading to common models for robustness evaluation.

17. Create an interoperable framework for enterprise models that supports manufacturing and business decision-making across the extended enterprise.

18. Develop and execute strategies to integrate M&S as "the way business is done" into Acquisition & O&M culture.

19. Provide structure that supports repartitioning across disciplines, providing different views and configurations, with different systems interfaces.

20. Make M&S pervasive across the organization, including establishing ROI requirements, maximizing revenue opportunities, and managing risk.

21. Develop a modeling capability that refines preferences to create definitive design parameters/objectives in a trade-off environment.

22. Make M&S infrastructure and environment be understood as the primal and most strategic investment analysis tool in the organization. Gain support for M&S approach by showing proof.

23. To accommodate different users' requirements at different times/contexts, provide user interfaces that are dynamically reconfigurable according to the context of use and that include accommodating the type of device being used (PC, phone, etc.).

24. Develop mechanisms to support verification and validation for materials and manufacturing process simulations.

25. Develop and deliver M&S capability to determine, in design phase, the life-cycle cost/risk/performance impacts of decisions about reliability, maintainability, supportability, etc.

26. Develop technologies and tools enabling integration of real-time data into life-cycle models.

27. Develop and deliver technologies enabling model-based control of life-cycle functions.

28. To minimize training and maximize decision-making efficiency, provide a generic GUI/cockpit/dashboard for the operation of multiple, heterogeneous distributed models with multiple levels of utility/complexity.

29. Develop the methodology/interface for systematically translating requirements for material selection.

30. Create methodologies for the mitigation of risk for the selection of new materials.

31. Develop a comprehensive virtual test environment integrating all life-cycle factors and considerations.

32. Develop and implement techniques and technologies driving evolution of an M&S enabled and empowered workforce.

33. Develop test methods to arrive at and validate methods of interoperability.

34. Provide intuitive systems that represent the human decision process and enable effective interaction with modeling systems.

35. Mature and expand existing simulation technologies to be used by practitioners to make underlying technology more transparent.

36. Develop multi-dimensional object-oriented cost models (models carry all elements of cost).

37. Dramatically reduce the amount of time and labor and expertise required to develop, populate, and use integrated models and simulations to reach a feasible, producible solution.